Manuscript Details

Manuscript number	ECSS_2017_547_R1
Title	The effect of vegetation height and biomass on the sediment budget of a European saltmarsh
Article type	Research Paper

Abstract

Sediment retention in saltmarshes is often attributed to the presence of vegetation, which enhances accretion by slowing water flow, reduces erosion by attenuating wave energy and increases surface stability through the presence of organic matter. Saltmarsh vegetation morphology varies considerably on a range of spatial and temporal scales, but the effect of different above ground morphologies on sediment retention is not well characterised. Understanding the biophysical interaction between the canopy and sediment trapping in situ is important for improving numerical shoreline models. In a novel field flume study, we measured the effect of vegetation height and biomass on sediment trapping using a mass balance approach. Suspended sediment profilers were placed at both openings of a field flume built across-shore on the seaward boundary of an intertidal saltmarsh in the Dengie Peninsula, UK. Sequential removal of plant material from within the flume resulted in incremental loss of vegetation height and biomass. The difference between the concentration of suspended sediment measured at each profiler was used to determine the sediment budget within the flume. Deposition of material on the plant/soil surfaces within the flume occurred during flood tides, while ebb flow resulted in erosion (to a lesser degree) from the flume area, with a positive sediment budget of on average 6.5 g m-2 tide-1 with no significant relationship between sediment trapping efficiency and canopy morphology. Deposition (and erosion) rates were positively correlated to maximum inundation depth. Our results suggest that during periods of calm conditions, changes to canopy morphology do not result in significant changes in sediment budgets in marshes.

Keywords	Erosion; deposition; trapping efficiency; flume; inundation; Spartina
Taxonomy	Coastal Geography, Coastal Vegetation, Coastal Erosion

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Suggested reviewers	Stefanie Nolte, Kerrylee Rogers, Cai Ladd, Kelly Elschot

Submission Files Included in this PDF

File Name [File Type]

Letter_REEF.pdf [Cover Letter]

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MONASH University

Dr Ruth E Reef
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4 August 2017

Dear Editor
Estuarine, Coastal and Shelf Science,

We believe that the attached manuscript ("The effect of vegetation height and biomass on the sediment budget of a European saltmarsh") will have broad interest for the readers of ECSS as an original research paper.

There is growing concern about the fate of coastal ecosystems, particularly under the projections of sea level rise and the concurrent threats imposed by human modification of the coastal zone. Numerous reports point to the need to manage coastal catchments to prevent accelerating losses of coastal habitats with sea level rise and for the protection of communities. Saltmarshes are widespread globally and are important for coastal hazard mitigation and climate change adaptation through their ability to stabilize shorelines and through vertical accretion, which is determined by the accumulation of mineral and organic matter. In this study we examined the effects of the saltmarsh canopy on sediment deposition and erosion in a unique and novel field flume setting.

Our findings are highly relevant for numerical modelling of estuarine and coastal marine ecosystems. We find that during calm summer conditions, due to low vertical mixing of the water column, the morphology of the saltmarsh canopy has no influence on sediment trapping efficiency. We find significant and clear relationships between inundation time and deposition. Both these finds simplify our ability to model accretion and erosion in these environments. We also present a detailed sediment budget for the East Anglian saltmarsh with a unique, high temporal resolution.

All authors have materially participated in the research and the article preparation and have approved the final article. Conflicts of interest: none.

We look forward to your decision on the suitability of our work for publication in Estuarine, Coastal and Shelf Science.

Sincerely,

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24/11/2017

Dear Prof Elliott,

Thank you for the opportunity to revise our manuscript (ECSS_2017_547) for publication in ECSS. We have addressed the reviewers' comments below. Those comments are in normal font, and our responses are in **bold** format. Changes are also indicated in the manuscript using 'track changes'.

Sincerely,

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-Reviewer 1

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The study presents a very interesting approach to measure sedimentation based on the budget in a field flume. However, due to the study design I have some questions regarding the statistics and the conclusions drawn from the results. Apart from that, the paper is very well written.

We have consulted with a statistician from the Monash Academy for Cross & Interdisciplinary Mathematical Applications (Dr Memet Ozman) and have revised some of the statistical approaches here (which did not have an affect of the interpretation of the results)

Please find detailed comments below:

Introduction:

Paragraph 2:

The paragraph has been rewritten to address the points brought up by both reviewers:

> **"The presence or absence of vegetation, as well as vegetation parameters such as height and biomass are thought to be key factors in determining rates and patterns of sediment trapping and deposition, although this relationship is non-linear (Nardin and Edmonds, 2014) and may be dependent on wave and flow conditions. The importance of vegetation structure in marsh functioning is well recognised but its incorporation in realistic representations of the interactions between vegetation and sedimentation is complicated by the immense variability in canopy structure on a range of scales. Marsh vegetation shows great inter-specific variability in stem flexibility (Tempest et al., 2015; Rupprecht et al., 2017) affecting plant-flow interactions and sedimentation. Furthermore, marsh vegetation is regularly subjected to both emergent and submerged states and, in the case of the latter, to both 'normal' and extreme 'storm surge' flow regimes. Vegetation height and biomass varies both spatially and temporally on European saltmarshes. Such canopy characteristics vary with intertidal elevation (Silvestri et al., 2005) and with the seasons. Communities are typically composed of a combination of perennial and annual species with little above ground presence during winter (Watkinson and Davy, 1985) when annual species are absent and perennial saltmarsh species biomass is also much reduced (Hussey and Long, 1982; De Leeuw et al., 1990). Biomass reaches a peak at the end of the northern summer growing season (De Leeuw et al., 1990). In the longer term, saltmarsh canopy height and biomass vary as a function of climate change (Arp et al., 1993; Reef et al., 2016) and eutrophication (Deegan et al., 2007). "**

- In the sentence starting with 'Marsh vegetation shows', the second part of the sentence seems to be unconnected to the first. Could you please clarify.

This has been completely rewritten to clarify the premise of this paragraph which focuses on the causes of the high variability in canopy structure over spatial and temporal scales.

- In sentence 3, what is meant by 'intertidal position'? Is this the marsh zone (low marsh, high marsh etc.)?

Changed to 'elevation' (many UK marshes exhibit a continuum of species as a function on elevation rather than organisation into two distinct zones).

- Sentence 4. I don't agree that communities are typically composed of many annual species. This might be true for a pioneer marsh with mainly Salicornia, but other marsh zones are typically also including many perennial species such as grasses, forbs (Aster) and small shrubs (Atriplex).

This has been re-written to read: "Communities are typically composed of a combination of perennial and annual species with little above ground presence during winter (Watkinson and Davy, 1985) when annual species are absent and perennial saltmarsh species biomass is also much reduced (Hussey and Long, 1982; De Leeuw et al., 1990)."

- Last sentence: What is meant by 'sensitive' to climate change?

Rewritten: "In the longer term, saltmarsh canopy height and biomass vary as a function of climate change (Arp et al., 1993; Reef et al., 2016) and eutrophication (Deegan et al., 2007). "

Paragraph 3:

- This paragraph is a bit unconnected to the one before. This might already be fixed by adding 'in vegetated areas' after 'flow rates'.

Corrected, thank you

- I would add Spencer (2016) 'Salt marsh surface survives true-to-scale simulated storm surges' in this paragraph and in the discussion.

Added, thank you

- In the end of the paragraph you state that only few studies tested the efficiency with which salt marshes trap tidally advected material. How is this a knowledge gap? And you also (only) test one salt marsh and one vegetation type. I would therefore prefer a more precise aim or hypothesis. The present aim is a bit vague.

The gap pertains to the lack of field experiments, as most of these studies are done in flumes where all other natural variations are removed. The sentence has been amended to reflect this:

"In this study, we aim to close this knowledge gap of the role of vegetation structure on deposition *in situ* through the use of a field flume, in combination with a mass balance approach to determine how changes to canopy morphology affect trapping efficiency in a UK saltmarsh."

Methods:

- Sediment budget measurements. How often did you take a sample with the water sampler?

We took three water samples at each inundation event (30 minutes apart) over 8 consecutive inundations (~2 inundations per day over four days). This has been clarified in the text which now reads:

"In order to calibrate the ASM sensor turbidity readings to g m^{-3}, water samples (1 L) were collected at 4 cm above the marsh surface using an automated water sampler (ISCO 6712, Teledyne Isco, Lincoln NE, USA) in the pioneer zone of the saltmarsh during two spring tide periods in April (7-11 April 2016) and July (21-24 July 2016). In each calibration period, three samples were taken, 30 minutes apart, during each inundation over eight consecutive inundations (N=24). Following collection, the samples were filtered through pre-weighed GF/C filters, which were then dried at 105°C for 24 hours and re-weighed. Measured sediment concentrations in the water samples were compared to the simultaneously measured turbidity levels recorded by both ASM IV at 4 cm above the

marsh surface. A calibration curve was derived for each of the devices, relating turbidity to suspended sediment concentrations (SSC) (R^2=0.91, Fig. S1)."

- Canopy height: How exactly was this measured?

Canopy height was measured using scale calibrated (at 8 different locations along the flume) horizontal, sideways looking, photos taken along the entire flume length transect. The canopy (green) was easily distinguished digitally from the flume wall background (light tan) using a grey scale threshold. A line plot was then created from the threshold edge and digitised (and scale calibrated) so that the y-axis was height above bottom in cm and the x axis was cm from flume opening along the ground. Further analyses included average height, maximum height and standard deviations. This has been clarified in more detail in the text.

"In order to quantify the effect of plant canopy morphology on the saltmarsh sediment budget, we reduced the height of the vegetation in the flume by ca. 5 cm every other inundation (Fig. 2A). The cut material was collected, dried (48 hours at 105°C) and weighed for biomass determination (Fig. 2B). Four cuts were carried out, reducing the mean canopy height from 10.7 cm (range 0-27 cm) to a final mean height of 1.3 cm (range 0-5.4 cm). Canopy height was measured across the entire flume area, using eight, scale calibrated, side-on photographs {Rupprecht, 2015 #2431} and analysed using line graph analysis (Image J, Schneider et al., 2012). The canopy (green) was easily distinguished digitally from the flume wall background (light tan) using a grey scale threshold. A line plot was then created from the threshold edge and digitised (and scale calibrated) so that the y-axis was height above bottom in cm and the x axis was cm from flume opening along the ground. Vegetation stem density was measured by manually counting stems in five 20 cm x 20 cm quadrats within the flume. "

Statistical analysis:

I have some questions about your ANCOVA that I would like you to address.

Following discussion with a statistical advisor, it was deemed that due to a lack of a relationship between water depth and vegetation height (see below), a multiple regression model would be better suited for data analysis. This has been amended throughout.

- Did you check the assumptions? Please have a look at Zuur (2010) A protocol for data exploration to avoid common statistical problems.

We did, but failed to report this. This has been corrected in the text, now in reference to multiple regression.

- Are vegetation height/biomass (your independent variables) correlated to maximum water level (covariate)? It looks like that because of the study design. For the very high water levels, you only have the intermediate vegetation height. So basically, the study design in unbalanced. This might be a serious issue. If the two factors are not independent, it will not be possible to disentangle which of the factors is playing the bigger role, even if the idea of an ANCOVA is of course to control for the covariate. So please check all assumptions and also address this problem in the discussion.

There is no relationship between water depth and vegetation height (see plot below), multicollinearity is not leading to shared variances between water level and vegetation height. Thus, it was decided to proceed with an approach which is more suitable for our type of data (many vegetation cuts but few replicates per stage) which is a regression model. As the two approaches (ANCOVA and multiple regression) are essentially identical, there were no impacts on the interpretation of the results.

However, as explained in more detail below, if the effect of the hydrodynamic forcings is much greater than that of the vegetation, an effect of vegetation would not be detected, but this reflects the field setting and our discussion that under field conditions the role of vegetation height is small/undetectable relative to other forcings. This is reflected in the rewriting of the first sentence of the Discussion: "Our field study indicates that under calm summer conditions, tidal flooding delivers very fine sand to the lower marsh at Tillingham, Essex, which is deposited at a rate that is not demonstrably affected by canopy height and biomass"

- Another problem is the unbalanced design due to the missing data (which I am aware sometimes can't be avoided in the field). The ANCOVA calculates the slopes of the lines for each treatment. However, for two treatments (0.059m & 0.039m) there is only one point. So it's impossible to calculate a slope for these treatments. How does this affect your result?

I agree with the reviewer that it would have been better to have a more balanced design, but unfortunately we could not achieve that in the field. We have overcome this by using a multiple regression approach.

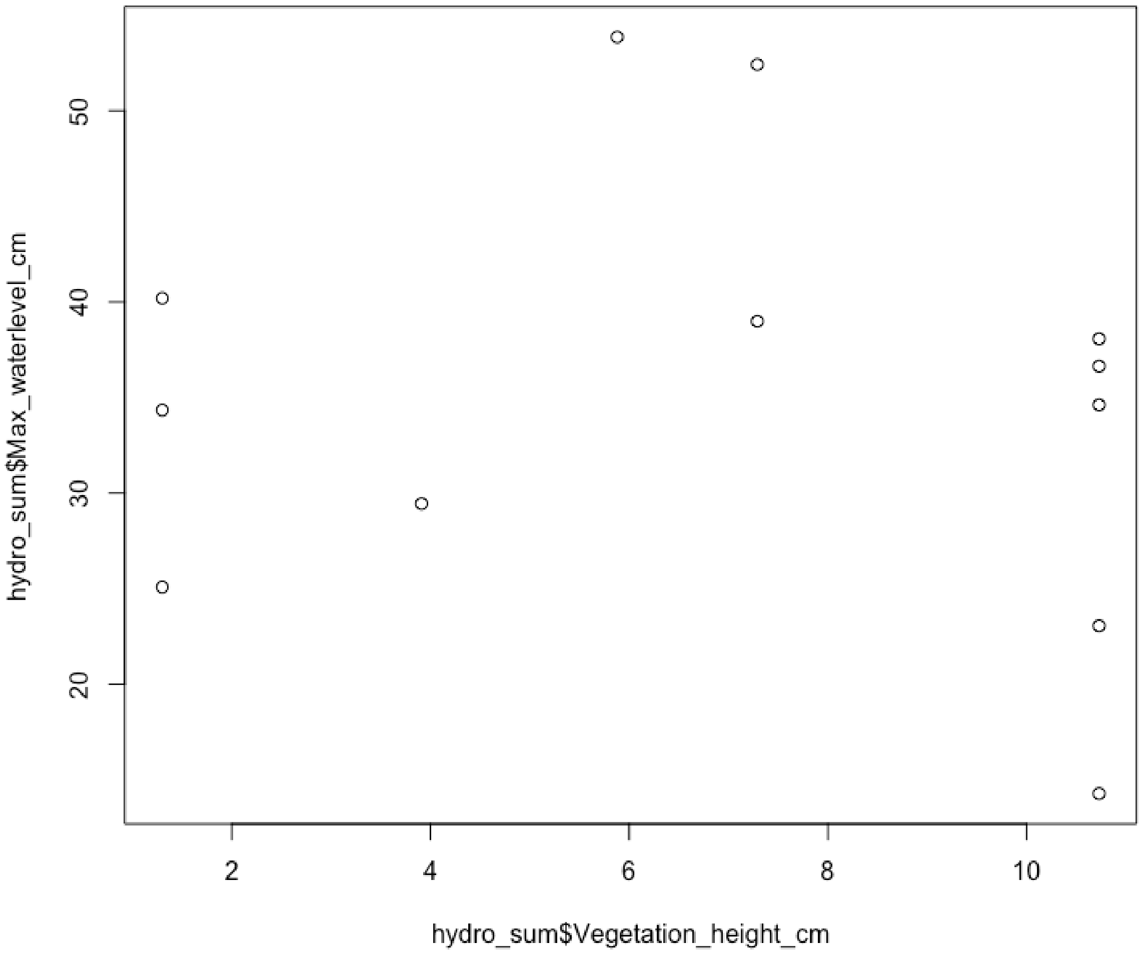
Results:

- A general remark, I realized you use different terms for the maximum water level throughout the manuscript (maximum inundation depth; Inundation maximum).

That is an oversight, sorry, the text has been amended to ensure consistency ('maximum inundation depth')

- Please add information on whether the mean maximum water level differs between vegetation height treatments.

In the statistics section it was added that there is no linear correlation between vegetation height and maximum water height (plot below). Vegetation height is already provided in Table 1 which has been amended to also include vegetation cut stage.



- Sediment budget (paragraph 1): The lack of a vegetation height effect might also be due to the study design (differences in max water level between vegetation height treatments). If the water levels differ by treatments, the water level might be the factor explaining all the variation which technically leaves no variation to be explained by your treatment (see above).

  That is correct. Many laboratory studies that keep all other factors constant (e.g. inundation height, flow speeds) find a significant effect of vegetation height on sedimentation, and this is also expected from a purely computational approach where the vegetation effect is isolated from other forces. What our study (and other field studies) show, is that the significant signal vegetation height might have, is undetectable in field conditions, where the hydrodynamic forces are so much more dominant than the vegetation effect, resulting in the vegetation effect is not detectable under these conditions even when looking for it with the best possible statistical tools (such as covariance analysis). Lab experiments provide the optimal testing conditions for detecting the relatively small effect of vegetation by minimising the signal/noise ratio, but the 'noise' in the natural environment should not be removed if we are to understand what is happening in field settings.

  The discussion has been rewritten to reflect this better (see below).

Discussion:

Paragraph 1:

- What is meant by ‘extrapolation through time’.

I agree that this adds confusion. It has been removed.

Paragraph 2:

- This paragraph nicely summarizes other studies which found or didn’t find an effect of the vegetation. However, it would be nice if you relate their explanations more clearly to the present study. You summarize this by the very last sentence, but I think it would be good to give the reader more details here.

The paragraph has been rewritten (see below)

- In addition to Elschot, Nolte (2015) ‘Effects of livestock species and stocking density on accretion rates in grazed salt marshes’ found an effect only in years with a high flooding frequency and generally high enough accretion rate. Is the seasonality possibly another reason why there was no effect? (Ah! I see that’s partly in the next paragraph.)

Yes it is, which is why our findings are confined to calm, summer conditions. Under winter conditions, when the sediment in the water column is better mixed we would hypothesise that there would be more accretion and a stronger vegetation response.

Paragraph 3:

- The sentence at the end might be the most important reason and I would therefore put it a bit earlier in the discussion.

I feel like the reader requires the information provided in paragraph 3 to accept the possibility depicted in the final sentence.

General points:

- The discussion does, to a larger degree, not include a debate about the potential problems with the study design. The seasonality is mentioned, but I think the repeated design with different maximum water heights are another big problem.

I have included reference to this by rewording the opening sentence to (“Our field study **indicates that under calm summer conditions, tidal flooding delivers very fine sand to the lower marsh at Tillingham, Essex, which is deposited at a rate that is not demonstrably affected by canopy height and biomass”) and by rewriting paragraph 2, which now reads:**

“Previous studies have compellingly shown that saltmarshes effectively attenuate tidal flows (Christiansen et al., 2000; Neumeier and Ciavola, 2004) and waves (Möller et al., 1999) as a function of vegetation density and height. However, potential linkages

between vegetation canopy characteristics and small scale turbulence around plant elements (Widdows et al., 2008), mean that there is not necessarily a direct link between hydrodynamic conditions measured at the larger (metre) scale, sediment trapping, and sedimentation on the marsh surface. Attempts to link either vegetation parameters, or hydrodynamic measures alone, to sedimentation, are unlikely to succeed where the latter is explainable only through the interaction of the former two. Thus, Boorman et al. (1998) found no correlation between vegetation height and sediment accretion at one Essex saltmarsh, but did find a correlation at another marsh, suggesting that the relationship between vegetation structure and sedimentation can be site dependent. Despite flow attenuation, Widdows et al. (2008) even found enhanced erosion and lower sediment accretion rates in the lower sparsely vegetated saltmarsh due to enhancement of near bed turbulence relative to bare mud patches as the flow enters *Spartina anglica* canopies. In a North American saltmarsh, Moskalski and Sommerfield (2012) show that deposition and sediment trapping efficiency are not related to plant stem density but rather to the distance from the creek and suspended sediment properties. Studies on grazing by small and large herbivores on saltmarshes found a significant impact of grazing on vegetation height, but no subsequent effect on sediment deposition (Elschot et al., 2013). Similarly, our study indicates that contrary to theoretical predictions, during calm conditions the role of canopy morphology in areas where vegetation is present, is marginal for sediment accretion *in situ*. Our field based sampling design was such that it might not have been possible to detect a small effect of vegetation structure on deposition due to the dominance of the effects of hydrodynamic forcings and other, unmeasured interacting factors influencing sediment settling and erosion in this environment, such as microtopography (Stribling et al., 2007) and/or bed shear strength characteristics (Howes et al., 2010). Theoretical and lab based flume experiments provide optimal conditions for the detection of vegetation effects, even if they are small, by minimising the naturally occurring variability in other hydrodynamic and geomorphological factors, leading to a possible overestimation of the role of vegetation structure on sedimentation *in situ* under some conditions. "

- Another thing I was wondering is why you decided to clip the vegetation and not maybe reduce the density? I know that it's impossible to do all, but as you mention the stem density this might be something to discuss.

Hydrodynamic numerical modelling for simulating deposition on marshes (e.g. Temmerman et al. 2005 and the Delft3D hydrodynamic model) requires both an input for vegetation density and for height. These model simulations show that flow is strongly controlled by the height of the vegetation. In this study we focused on height but we are planning similar experiments for parameterising the effects of vegetation density on inorganic sedimentation.

- This study has been done in a low zone, probably to ensure enough inundations. However, what would you expect to happen in other marsh zones/vegetation types?

It is hard to tell, because the control volume approach to sediment budget calculation relies on water movement through the flume, which could be very limited higher in the

marsh where flow rates are even slower than those measured here and are dominated by non-directional flow. I do not think this methodology would be suitable for higher in the marsh. While speculative, sedimentation in higher marsh zones (away from creeks) might be controlled by infrequent storm events rather than the regular tidal cycle. These events are too different in terms of wind and sea conditions to our study to extend our findings to those zones, but I would hypothesise that vegetation height would play a greater role under those conditions.

Figure 2a): Could you indicate the position of the filter traps here? This might be interesting.

I have, although we did not keep track of which filter was where within the flume but rather used an average value.

Figure 2b): Please remove the line connecting the dots.

I have included a model of a height/biomass relationship instead of the line, the equation of this relationship is now presented in the caption.

Figure 3): Please change the labels to the vegetation height as factor. Also for Fig 5.

The labels have been changed according to the similar comments from Reviewer 1

Figure 4): I would prefer a figure here comparable to the figures 3 and 5, with water level as they axis, sediment as the x axes and vegetation height/biomass as factors. This would fit your analysis.

The Figure the reviewer is suggesting is already in the manuscript (Fig 3). This plot is a different analysis to Figures 3 and 5, it depicts the sediment budget (ebb, flood and net) as a function of vegetation height/biomass.

Figure 6): During tide 2 there seems to be more SSC in higher parts of the profile. Was there a special whether condition? Which point is this in the other figures? Was the sedimentation higher during this event?

This is a very interesting observation, and it could potentially corresponds to higher wind/wave generated mixing. While there was only one such event during the summer flume period (so we did not discuss this), it did lead to us to designing a second experiment to investigate this further...

-Reviewer 2

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This manuscript does address an important knowledge gap. There has been speculation over the importance of plant height/density in sediment trapping, which is discussed well in paragraph starting at line 442. The study is novel and appropriate for Estuarine and Coastal Shelf Sciences.

Thank you

The main conclusion reached by the author in lines 549-550 state that "our findings suggest that…the rate of sediment trapping by saltmarshes is independent of canopy height or biomass". However I am not convinced the results section provides sufficient evidence to dismiss the effect vegetation height or biomass on sediment flux for the following reasons:

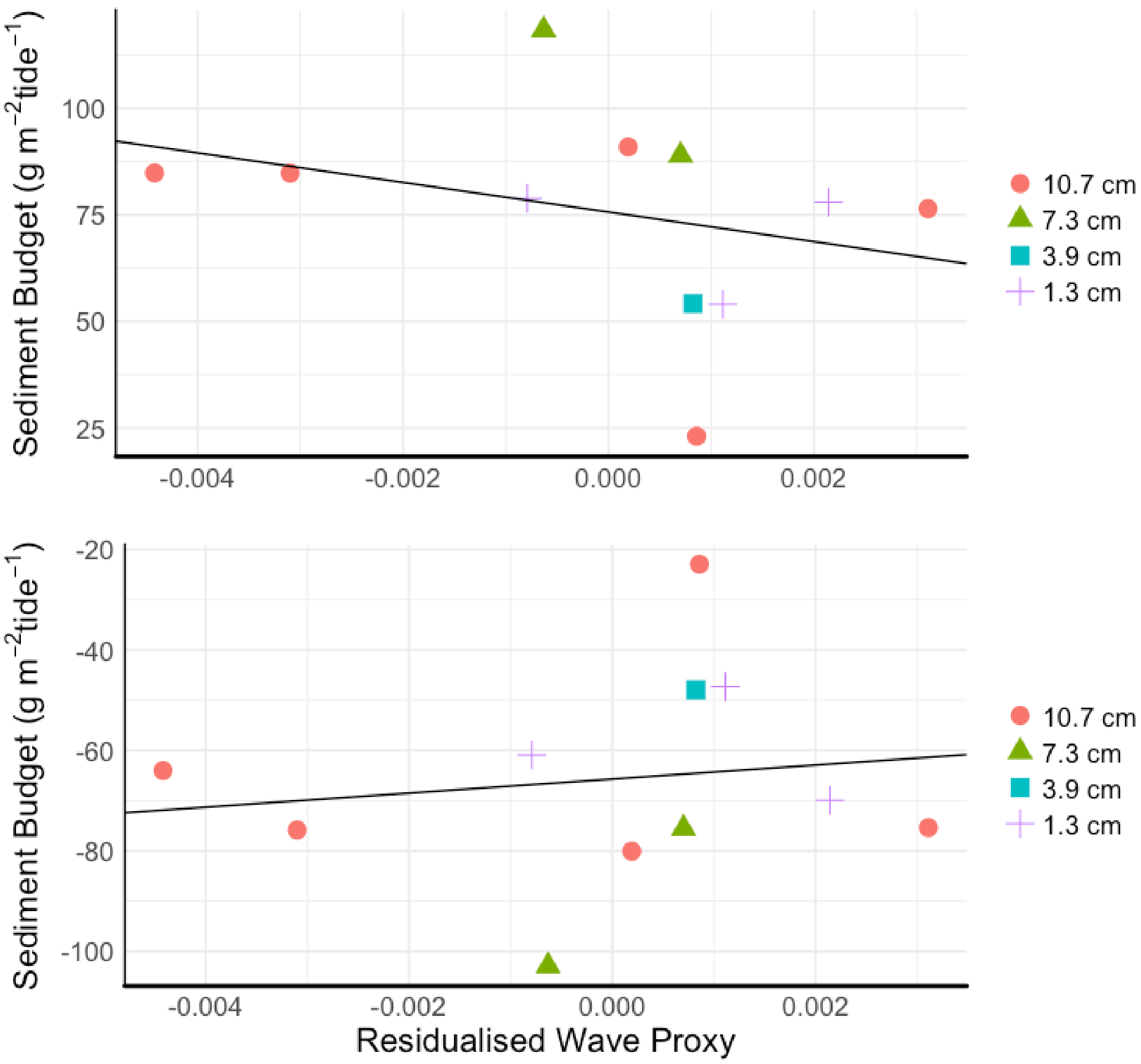
We have reworded this. See comments by Reviewer 1.

i. **The statistical analysis is not well described.** Like any statistical test, ANCOVA has a number of assumptions that need to be met before the model can be built, and the best-fit model once selected must be validated (i.e. for homogeneity of variance, outlier effect, overfitting etc.). There is no indication that the author ran any pre- or post-fitting analyses to test the robustness of the statistical model. Also, the results of the ANCOVA findings in the results sections are incomplete. The author does not state the degrees of freedom, and does not report the F-statistic (which tells us about the sample variance). I am also unclear of which statistical test is being used in some cases: In the results section (lines 377 and 399), the statistical test for figure 3 and 5 report using an ANCOVA, however in the respective figure text, the author states that "a linear regression model was fitted to the data". I would like to see a more robust statistical analysis and clearer description of the analysis used. I recommend reading Riggs et al. (2007), who have a section on ANCOVA model selection and validation (see 'model fitting issues' header and references therein), as well as Zuur et al. (2010) who describe methods for model selection.

We have consulted with a statistician (Dr Mehmet Ozmen from the Monash School of Maths) and incorporated the changes suggested. See above.

ii. **Low sample size / replication.** In total, the authors have 14 observations within 5 treatment levels. The number of observations varies between treatment level, in some cases with only a single data point (e.g. Fig. 3; Cut2). The author shows that covariates had an effect (as one would expect), but I am unclear how the author disentangled the effect of canopy height/biomass on sediment flux from the covariates water level / wave height proxy using this data. My specific concern here is that there is a lack of data spread across a range of water level / wave height proxies at each treatment level (vegetation heights), therefore it is not known whether the slope/intercept varies between treatments (indicating whether or not an effect of vegetation is present or not, independent of a given covariate). Another issue of the low sample size becomes apparent in figure 5: the fitted line appears to be heavily biased by the data point in 'Cut2', and it may be that the analysis (ANCOVA or Regression) produces a significant trend if this point were removed. I wonder if the model validation failed at this stage due to the effect of the outlier, invalidating the result stated in lines 396-402? Might there be a reason why 'Cut2' is an outlier, and if so could you possibly justify its removal?

We could not justify removing data point 'Cut 2'. Unlike other points that were affected by the structural failure of the flume (lack of rigidity when encountering bigger waves), 'Cut 2' was a measurement taken on a more windy day (which led to the warping of the flume in the following measurements as the waves picked up, but review of the time lapse camera photos shows the flume functioning and intact at this data point). However, even if removed, Figure 5 still shows no significant relationship between the sediment budget and the residualised wave proxy. A figure with 'Cut 2' removed is provided below:



I also have general criticism over some of the structure of the paper, wording and figures:

I hope the corrections below and in response to reviewer 1 have made the paper clearer.

- The statement "…with an earlier calibration period" in line 158 is out of place – calibration of what?

This has been corrected.

- The procedures used to process samples described in sections 'sediment budget measurements', 'vegetation canopy height and biomass manipulation' and 'measuring sediment deposition' of the methods section all require references to justify the method used. Ford et al. (2016) shares a number of similar methods, references therein could be used.

Sediment balance calculations using a mass balance approach is as far as I can ascertain, novel, and following careful reading of the Ford et al. (2016) paper, I cannot find overlap in methodology. The vegetation canopy height measurements using side-on photography shared a similar methodology to that validated in Rupprecht et al. (2015) and this citation has been added.

"Rupprecht, F., Möller, I., Evans, B., Spencer, T., Jensen, K., 2015. Biophysical properties of salt marsh canopies — Quantifying plant stem flexibility and above ground biomass. Coastal Engineering 100, 48-57."

- Lines 232-247 of the methods section should be moved to the results section.

The results of the vegetation cuts are presented in the results section. These lines present a 'site description'.

- Lines 293-306 of the results section should be moved to the methods section.

- In the 'statistical analysis' of the methods section, wave height proxy is not referred to as a covariate. Also, vegetation height/biomass are referred to as main effects (line 283), but are later referred to as covariates in line 397.

This has been corrected

- Results in the paragraph starting at line 308 and 315 are not linked to table 1.

Corrected

- In line 318, the PXT1830 pressure transmitter is referred to. This should be in methods section, as should lines 326-327.

Corrected

- It is unclear exactly when a cut to the vegetation was made. I think this information should be added to Table 1.

This has been added to Table 1

- In line 386, "inundation height" is linked to figure 4 but is missing in that figure.

The link has been removed

- I find the section in lines 396-401 difficult to follow. Please clarify.

Reading this again after not seeing the paper for a few weeks, I agree with the reviewer. I have rewritten the section.

- The map in figure 1A does not require a north arrow since a graticule is provided. The scale bar at the top of 1B is misleading because of image perspective. Better to state the distance between two objects in the text (e.g. distance between the two ASM profilers).

Corrected

- The legend in figure three should be arranged in a more logical order ('start' should be at the top)

The legends in figures 3 and 5 were amended to include vegetation height rather than 'cut' as suggested by Reviewer 1 and are now ordered more logically (from highest to lowest).

- For figure 5, would 'normalised' be a better descriptor than 'residualised'? Also the title 'wave proxy' refers to wave height, correct? Please clarify.

'Residualised' is a statistical term which is mathematically distinct from normalisation, it has now been better explained in the methods.

- I personally would find Figure 6 easier to interpret if the axes were reversed, but this may be personal preference.

Most stratified oceanographic data is presented in a vertical plot, I feel like this is more intuitive for the reader, but this is a matter of personal preference and I will accept the editors decision

I believe the main hurdle to overcome is the issues I raise in point i. I do not profess to be an expert of ANCOVA analysis, but I believe my concerns are fair having compared to other studies that use this technique.

They are fair concerns, I hope we have alleviated some of those with the amendments to the paper following our consultation with Dr Ozmen, the statistical consultant.

References

Riggs et al. (2007) Analysis of covariance models for data from observational field studies. *Journal of Wildlife Management.*

Zuur et al. (2010) A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution.*

Ford et al. (2016) Soil stabilization linked to plant diversity and environmental context in coastal wetlands. *Journal of Vegetation Science.*

The effect of vegetation height and biomass on the sediment budget of a European saltmarsh

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Keywords:
Erosion, deposition, Spartina, trapping efficiency, flume, inundation

Abstract

Sediment retention in saltmarshes is often attributed to the presence of vegetation, which enhances accretion by slowing water flow, reduces erosion by attenuating wave energy and increases surface stability through the presence of organic matter. Saltmarsh vegetation morphology varies considerably on a range of spatial and temporal scales, but the effect of different above ground morphologies on sediment retention is not well characterised. Understanding the biophysical interaction between the canopy and sediment trapping *in situ* is important for improving numerical shoreline models. In a novel field flume study, we measured the effect of vegetation height and biomass on sediment trapping using a mass balance approach. Suspended sediment profilers were placed at both openings of a field flume built across-shore on the seaward boundary of an intertidal saltmarsh in the Dengie Peninsula, UK. Sequential removal of plant material from within the flume resulted in incremental loss of vegetation height and biomass. The difference between the concentration of suspended sediment measured at each profiler was used to determine the sediment budget within the flume. Deposition of material on the plant/soil surfaces within the flume occurred during flood tides, while ebb flow resulted in erosion (to a lesser degree) from the flume area, with a positive sediment budget of on average 6.5 g m^{-2} $tide^{-1}$ with no significant relationship between sediment trapping efficiency and canopy morphology. Deposition (and erosion) rates were positively correlated to maximum inundation ~~heights~~depth. Our results suggest that during periods of calm conditions, changes to canopy morphology do not result in significant changes in sediment budgets in marshes.

Introduction

The balance between sea level rise and rates of sediment accretion is a key research question in the broader debate as to whether or not marsh surfaces will be able to keep up with near-future accelerated sea level rise (Orson et al., 1985; Kirwan et al., 2010). Sea level rise poses a threat to intertidal saltmarshes due to seawater inundation beyond the physiological tolerance of the vegetation. However, the ability of marshes to accrete vertically through sediment trapping and root growth allows them to maintain their position in the tidal frame as it is translated upwards, promoting their long-term stability and survival (Morris et al., 2002; French, 2006; McIvor et al., 2013). It has been argued that the presence of vegetation enhances sedimentation on saltmarsh platforms both by attenuating wave energy and slowing water flow (Boorman et al., 1998; Temmerman et al., 2005) and by preventing the resuspension of deposited sediments on, and the direct erosion of, saltmarsh surfaces (Fagherazzi et al., 2012).

The presence or absence of vegetation, as well as vegetation parameters such as height and biomass are thought to be key factors in determining rates and patterns of sediment trapping and deposition, although this relationship is non-linear ~~(Nardin and Edmonds, 2014)~~(Nardin and Edmonds, 2014) and may be dependent on wave and flow conditions. The importance of vegetation structure in marsh functioning is well recognised but its incorporation in realistic representations of the interactions between vegetation and sedimentation is complicated by the immense variability in canopy structure on a range of scales. Marsh vegetation shows great inter-specific variability in stem flexibility (Tempest et al., 2015; Rupprecht et al., 2017)~~,~~ affecting plant-flow interactions and sedimentation. Furthermore, marsh vegetation is regularly subjected to both emergent and submerged states and, in the case of the latter, to both 'normal' and extreme 'storm surge' flow regimes. Vegetation height and biomass varies both spatially and temporally on European saltmarshes. ~~Canopy~~Such canopy characteristics vary with intertidal ~~position~~elevation (Silvestri et al., 2005) and with the seasons. Communities are typically composed of ~~many~~a combination of perennial and annual species with little above ground presence during winter (Watkinson and Davy, 1985) when annual species are absent and perennial saltmarsh species biomass is also much reduced (Hussey and Long, 1982; De Leeuw et al., 1990). Biomass reaches a peak at the end of the northern summer growing season (De Leeuw et al., 1990). In the longer term, saltmarsh canopy height and biomass ~~appear sensitive to~~vary as a function of climate change (Arp et al., 1993; Reef et al., 2016) and eutrophication (Deegan et al., 2007).

While slower flow rates in vegetated areas enhance particle settlements and thus deposition (Neumeier and Amos, 2006), the movements of plants when acted on by waves and currents can scour the surface and significantly enhance erosion, particularly in the pioneer zone and along marsh seaward margins (Temmerman et al., 2007; Feagin et al., 2009). Sheehan and Ellison (2015) observed significantly lower accretion and higher erosion rates immediately following the complete removal of a saltmarsh vegetation cover, although the addition of organic matter to the soil substrate over time contributes to erosion-resistant soils (Feagin et al., 2009). Periods of increased erosion in UK saltmarshes coincide with periods of higher winds and wave heights (van der Wal and Pye, 2004; Wolters et al., 2005); this may also cause increased sedimentation on the saltmarsh platform (Schuerch et al., 2012). There are, however, relatively few studies worldwide on the efficiency with which saltmarshes trap tidally advected material ~~(French, 2006; Moskalski and Sommerfield, 2012; van der Deijl et al., 2017).~~in field conditions (French, 2006; Moskalski and Sommerfield, 2012; Spencer et al., 2015b; van der Deijl et al., 2017). In this study, we aim to close this knowledge gap of the role of vegetation structure on deposition *in situ* through the use of a field flume, in combination with a mass balance approach to determine how changes to canopy morphology affect trapping efficiency in a UK saltmarsh.

Methods

Setting and physical environment

The field study was undertaken on the UK east coast at Tillingham, Dengie Peninsula, (51.69425°N 0.94206°E, Fig. 1A) between the estuaries of the Rivers Blackwater and Crouch. The saltmarsh is a near-horizontal platform of clayey silts, ca. 200 m in width, at an elevation of 1.9 - 2.5 m above Ordnance Datum Newlyn (ODN; where 0.0 ODN approximates to mean sea level). The tidal mudflat immediately seaward of the marshes are at elevations of 0.9 - 1.9 m ODN and show a 'mudmound topography' of shore-normal sinuous ridges and runnels in the transition zone between the saltmarsh and the flat tidal mudflat. The runnels narrow shorewards into small creeks which dissect the marsh surface (Möller and Spencer, 2002). The Dengie Peninsula coast is macrotidal, with a mean spring tidal range of 4.8 m (Reed, 1988). The southern North Sea is, however, particularly susceptible to storm surges which raise water levels well above expected tidal levels. ~~Thus the storm surges of 1953 and 2013 reached 4.4 m ODN at West Mersea, Blackwater estuary (Spencer et al., 2015), resulting in water depths of ca.~~Thus the storm surges of 1953 and 2013 reached 4.4 m ODN at West Mersea, Blackwater estuary (Spencer et al., 2015a), resulting in water depths of ca. 2 m over marsh surfaces. The wave climate is moderate with a maximum recorded significant wave height (H_s) of 0.65 m at Sales Point on the northern limit of the Peninsula (Herman, 1999).

The main sediment sources for the marshes in East Anglia are thought to be the erosion of coastal cliffs in Norfolk and Suffolk, and to a much lesser extent, fluvial inputs from East Anglian rivers, and offshore seabed erosion (McCave, 1987). The cliff sediments are unconsolidated Quaternary sediments with a high proportion of inorganic mud. Suspended sediment concentrations in the southern North Sea are highly seasonal, with more than a fourfold increase in sediment concentrations in winter compared to summer (Prandle et al., 1997). Our experiment was undertaken during summer, when sediment supply to the marsh is lowest, but vegetation biomass is highest.

Experimental design

The experiment was carried out during the spring tide period between the 2-9 July 2016~~, with an earlier calibration period between the 7-11 April 2016.~~. We selected an area towards the seaward fringe of the saltmarsh at Tillingham and enclosed it within a plywood flume channel secured to the marsh surface with wooden stakes. The flume was 1000 mm in width, 1820 mm in length and the vertical walls were 900 mm high, with symmetrical funnel shaped openings at each end (Fig. 1B). It was placed across-shore (E-W), corresponding to the main direction of tidal flow. One profiling turbidity sensor (Argus

Surface Meter (ASM) IV) and one pressure sensor (Solnist Levellogger Edge, Model 3001) were placed in the centre of both openings. The ASM IV turbidity profilers are titanium rods consisting of a series of 144 optical backscatter (OBS) sensors arranged as an array, with a 10 mm vertical spacing. The profilers and pressure sensors were programmed to record a depth-averaged turbidity profile (10 measurements over 10 s) and a water depth every 30 seconds

Hydrodynamic measurements

The hydrodynamic conditions during the experiment were primarily deduced from the water levels recorded by the pressure sensors. The continuous (or still) water levels and the maximum tidal inundation ~~heights~~depth were derived from a smoothed water level curve, which was calculated using a moving-average filter with a window size of 15 minutes (=30 data records). A proxy for wave heights was calculated for every tidal inundation as the standard deviation of the differences between the recorded and the still water level (smoothed water level curve) and validated with actual wave measurements, using a PTX1830 pressure transmitter (Möller, 2006) during a previous measurement campaign. Validation of the wave proxy resulted in a highly significant correlation between the wave proxy calculated from the smoothed water curve and the measured wave heights measured using the PTX1830 of the form (*wave height (cm)* =6.465 x *wave proxy*, R^2=0.92, p<0.001). Wind conditions were obtained from two UK Met Office coastal meteorological stations in Essex, one at Walton-on-Naze and one at Shoeburyness (Southend-on-Sea). Average daily wind speeds (measured at Walton-on-Naze, Essex and at Shoeburryness, Essex) ranged between 10 and 21 km h^{-1} with a predominant W/SW direction (UK Met Office, www.metoffice.gov.uk).

Sediment budget measurements

~~Water~~In order to calibrate the ASM sensor turbidity readings to g m^{-3}, water samples (1 L) were collected at 4 cm above the marsh surface using an automated water sampler (ISCO 6712, Teledyne Isco, Lincoln NE, USA) in the pioneer zone of the saltmarsh during two spring tide periods in April (7-11 April~~) and July (21-24 July).~~ 2016) and July (21-24 July 2016). In each calibration period, three samples were taken, 30 minutes apart, during each inundation over eight consecutive inundations (N=24). Following collection, the samples were filtered through pre-weighed GF/C filters, which were then dried at 105°C for 24 hours and re-weighed. Measured sediment concentrations in the water samples were compared to the simultaneously measured turbidity levels recorded by both ASM IV at 4 cm above the marsh surface. A calibration curve was derived for each of the devices, relating turbidity to suspended sediment concentrations (SSC) (R^2=0.91, Fig. S1).

A sediment budget for each tidal stage (flood and ebb phase) was calculated by numerical integration of the depth-averaged SSC difference between the upstream and downstream ASM sensors (g m^{-3}) over the instantaneous volume within the flume (m^3), using the trapezoidal rule. From the two ASM sensors at each end of the flume, the upstream and downstream sensors were assigned based on the tidal stage (i.e. the seaward sensor was assigned as the upstream sensor during the flood tide and as the downstream sensor during the ebb tide). Due to negligible flow velocities during slack water, we excluded the data from the slack tide period from our analysis. Slack tide was defined as the period where the rate of change of the smoothed water depth curve was <3.3×10^{-3} cm s^{-1}. Furthermore, data from water depths of <3 cm within the flume were excluded because of increasing relative measurement errors for small water depths.

A positive sediment budget denoted sediment deposition within the flume, whereas a negative value indicated erosion. The sediment budget was defined as the amount of sediment that was actually retained within the flume over the tidal cycle. Assuming an insignificant change in the amount of material held on plant surfaces, this should closely match the deposition data recorded by the GF/C filters deployed on the bed within the flume~~.~~ (see below).

Vegetation canopy height and biomass manipulation

The vegetation within the flume consisted of a typical '*Spartina alterniflora* saltmarsh community' (British NVC, SM5) dominated by *Spartina alterniflora* (50 % cover), *Aster tripolium* (17 % cover) and *Puccinellia maritima* (10 % cover) with some individuals of annual *Salicornia* spp. (5 %), *Suaeda maritima* (3 %) and *Atriplex portulacoides* (1 %). Vegetation ground cover in the flume was 86 %. Initial vegetation height within the flume was on average (± SD) 10.7 cm (± 2.2) with a maximum height of 26.7 cm (± 3.4) (Fig. 2). The 75th percentile was on average 15 cm (± 2.7). Average stem density was 910 stems m^{-2} (± 240) within the flume.

In order to quantify the effect of plant canopy morphology on the saltmarsh sediment budget, we reduced the height of the vegetation in the flume by ca. 5 cm every other inundation (Fig. 2A). The cut material was collected, dried (48 hours at 105°C) and weighed for biomass determination (Fig. 2B). Four cuts were carried out, reducing the mean canopy height from 10.7 cm (range 0-27 cm) to a final mean height of 1.3 cm (range 0-5.4 cm). ~~Canopy height was measured across the entire flume area, using scale calibrated photographs and analysed using line graph analysis (Image J, Schneider et al., 2012).~~Canopy height was measured across the entire flume area, using eight, scale calibrated, side-on photographs (Rupprecht et al., 2015) and analysed using line graph analysis (Image J, Schneider et al., 2012). The canopy (green) was easily distinguished digitally from the flume wall background (light tan) using a grey scale threshold. A digitised line plot was then created from the threshold edge so that the y-axis was height above bottom in cm and the x axis was cm from flume opening along the ground. Vegetation stem density was measured by manually counting stems in five 20 cm x 20 cm quadrats within the flume.

Measuring sediment deposition

Five glass petri dishes, inserted level with the soil surface, were evenly distributed within the flume~~.~~ (Fig. 1B). Pre-weighed glass fibre (GF/C) papers (9 cm diameter) were placed on the surface of each petri dish and held in position with small metal pins. The filters were exchanged every other tidal inundation and the dry weight of sediment deposited on the filters was measured after drying at 105°C for 24 hours.

The sediment characteristics (grain size and organic carbon content) were determined using hardened ashless filter papers (Whatman, Grade 540) distributed on the marsh, as above, during the 4-day July calibration period. The filters were then dried at 105°C for 24 hours and weighed, before being combusted at 505°C for 6 hours to burn away the filter paper and to determine sediment loss-on-ignition. The remaining sediment was weighed to determine the loss-on-ignition, representing the organic carbon content and analysed for grain size, using a Malvern Mastersizer 2000.

Statistical analysis

~~In order to control for variation in the hydrodynamic conditions amongst tides, the~~The relationship between vegetation height or biomass and deposition was measured using ~~analysis of covariance (ANCOVA)~~multiple linear regression with vegetation height (or biomass~~ as the main effect (categorical variable~~) and the hydrodynamic variable, maximum water level, as the ~~covariate~~predictors and deposition as the dependent variable. The two co-variates, maximum water level and vegetation height were not linearly correlated (p=0.65), satisfying the assumption of independence. To measure the effect of waves on deposition, we used a multiple regression model with wave proxy and vegetation height as predictors of deposition. Due to the collinearity of wave proxy and maximum water depth, we residualised wave proxy by running a preliminary regression analysis between wave proxy and maximum inundation depth and used the residuals from this analysis (wave proxy$_{resid}$) in lieu of wave proxy in the multiple regression model. For all linear models, the normality assumption was tested by the visual inspection of the histograms of the model residuals.

Results

Hydrodynamic and sediment characteristics

During the duration of the experiment (2-9 July 2016), we measured 14 tidal inundations over a set of rising and then falling spring tides, peaking on 7 July 2016 with a predicted high water level of 2.01 m (ODN) at Harwich, Essex, 40 km NE of the study site~~.~~ (Table 1). Mean High Water Springs (MHWS) at Harwich is 1.99 m ODN and Highest Astronomical Tide (HAT) is 2.44 m ODN. Due to flume damage on 6 July 2016, we had to remove tides 9 and 10 (6 and 7 July 2016) from the dataset.

Maximum inundation depths in the flume for each tidal inundation during the period of the experiment ranged from 0.14 m to 0.54 m~~.~~ (Table 1). The highest inundation depths were measured during tides 7 and 8 with 0.52 and 0.54 m respectively. With a maximum profiling range of 1.44 m, the observed inundations allowed for the capture of a complete turbidity profile during every tide.

The wave activity during the experiment, as represented by the wave proxy, was closely, positively correlated with the maximum inundation depth (r = 0.86), apart for tide 8. ~~Validation of the wave proxy resulted in a highly significant correlation between the wave proxy and the measured wave heights, using the PTX1830 pressure transmitter (*wave height*~~

~~(cm) =6.465 x *wave proxy*, R^2=0.92, p<0.001).~~ The highest wave proxy value occurred during tide 7 with the lowest values being observed during the first two tides (Table 1). ~~Average daily wind speeds (measured at Walton-on-Naze, Essex and at Shoeburryness, Essex) ranged between 10 and 21 km h^{-1} with a predominant W/SW direction (UK Met Office, www.metoffice.gov.uk).~~

Depth-integrated tidal horizontal velocities within the flume were approximated by the rate of change in water depth between measurements (rising velocity). On average the peak rising velocity during flood tides was 0.64 cm s^{-1}, whereas the average peak rising velocity during ebb tides was -0.57 cm s^{-1} (Table 1). The absolute highest rising velocity recorded was 0.90 cm s^{-1} during the flood of tide 8. During most of the observed tides the maximum rising velocity during flood tides was higher than during ebb tides (flood : ebb ratio >1) indicating a flood dominant inundation regime (Table 1). The most pronounced flood dominance was observed during tide 6, whereas tides 2 and 13 were the only tides showing ebb dominance (flood : ebb ratio < 1).

The sediment that settled on the filters in the flume during the calibration period was primarily composed of very fine sand (D_{50} = 121.9 µm, skewness = -0.19) and contained, on average (±SD), 15.4 % ±4.9 % organic matter.

Table 1: Hydrodynamic characteristics of the different flume inundation periods during the experiment. ~~mab = meters above bed.~~

Tide	Vegetation Height (m)	Vegetation Cut	Maximum Inundation ~~Maximum (mab~~Depth (m)	Max Flood Velocity* (cm s^{-1})	Max Ebb Velocity* (cm s^{-1})	Flood/Ebb Ratio	Wave proxy
1	0.107	Start	0.143	0.338	0.322	1.049	0.149
2	0.107	Start	0.231	0.470	0.473	0.993	0.232
3	0.107	Start	0.346	0.614	0.587	1.046	0.355
4	0.107	Start	0.366	0.677	0.579	1.169	0.369
5	0.107	Start	0.381	0.684	0.563	1.215	0.386
6	0.073	Cut 1	0.390	0.743	0.608	1.222	0.396
7	0.073	Cut 1	0.524	0.848	0.742	1.143	0.529
8	0.059	Cut 2	0.539	0.916	0.753	1.215	0.342
11	0.039	Cut 3	0.294	0.641	0.542	1.182	0.300
12	0.013	Cut 4	0.402	0.698	0.601	1.161	0.406
13	0.013	Cut 4	0.251	0.461	0.491	0.940	0.257
14	0.013	Cut 4	0.34	0.63	0.58	1.10	0.351

* Tidal horizontal velocities within the flume were approximated by the rate of change in water depth between measurements (rising velocity).

Sediment budget

The sediment budgets (deposition minus erosion of sediment) of the flood and the ebb periods for the flume area were both significantly affected by the maximum water level

(~~ANCOVA, t = 5.3~~multiple linear regression, β = 1.94, p < 0.001, R^2 = 0.74 and ~~t = -4.88~~β = -1.57, p < 0.001, R^2 = 0.72 for flood and ebb periods respectively, Fig. 3), but not by the height of the vegetation. Vegetation height was not a significant factor for sediment budgets in either flood or ebb periods (~~ANCOVA, t = 0.96~~β = 1.2, p = 0.22, R^2 = 0.74 and ~~t~~β = -1.~~68~~35, p = ~~-~~0.~~13,~~12, R^2 = 0.72 respectively, Fig. 4A). Vegetation biomass, which showed a non-linear reduction in relation to vegetation height (Fig. 2B) was also found to have no significant effect on the sediment budget during flood and ebb flows (~~ANCOVA, t~~multiple linear regression, β = 0.~~93~~007, p = 0.~~38~~21, R^2 = 0.74 and ~~t = -1.16~~β = -0.007, p = 0.~~28~~14, R^2 = 0.72, respectively, Fig. 4B). The net sediment budget following a full inundation cycle was not affected by maximum inundation ~~height~~depth, vegetation height or vegetation biomass (~~ANCOVA, t=2.~~β = 0.36, p = 0.07; β = -0.09, p = 0.~~07; t = -~~85, R^2 = 0.19~~, p = 0.85; t = -0.15~~; β = -0.00007, p = 0.~~89~~97, R^2 = 0.19; respectively~~, Fig. 4~~).

The sediment budget within the flume following each stage of the tide (Fig. 4) indicated sediment import into the flume area during the flood period (42.7 ± 13.53 g m^{-2}), and export from the flume area during the ebb period (-36.6 ± 11.15 g m^{-2}). Import during the flood was consistently greater than export during the ebb periods throughout the measurement period. Hence, the net sediment budget per tide was on average positive (6.1 ± 3.98 g m^{-2}).

~~An analysis of covariance~~A multiple linear regression with the ~~hydrodynamic variables maximum water level and~~residualised wave proxy ~~as factors~~ and vegetation height as ~~a covariate~~predictors, found that the wave proxy was not a significant ~~independent~~ forcing on the sediment budgets during flooding~~, but rather reflected the sediment deposition correlation to inundation periods~~ (Fig. 5A, ~~ANCOVA, t = 1.19~~multiple linear regression, β = 88.4, p~~=~~ = 0.~~27). However, the wave proxy explained some of the variability in the sediment budgets~~60, R^2=0.03) nor during ebb flows (Fig. 5B, ~~ANCOVA, t = -2.5, R^2 = 0.84~~β = -126.3, p = 0.~~039~~35, R^2 = 0.11).

The amount of sediment deposited on the filter traps within the flume was not significantly affected by canopy height (R^2 = 0.01, p = 0.79). There was no correlation between the mass of the sediment deposited on the filter traps and the mass balance calculation of net sediment budgets within the flume (Pearson's r = 0.26), but a high correlation was observed between sediment trapping on the filter and sediment deposition within the flume during flood periods calculated using the mass balance approach (Pearson's r = 0.72).

Sediment concentrations were significantly higher closer to the marsh surface than higher in the water column (Fig. 6). The mean SSC in the bottom 5 cm was more than 10 times higher than that measured for the rest of the water column (t-test, p<0.001). This pattern was more pronounced for the seaward sensor (Fig. 6A) than for the landward sensor (Fig. 6B). For both sensors, only tide 2 showed the presence of suspended sediment within the middle and upper parts of the water column.

Discussion

Our field study indicates that under calm summer conditions, tidal flooding delivers very fine sand to the lower marsh at Tillingham, Essex, which is deposited at a rate that is ~~independent of~~not demonstrably affected by canopy height and biomass. The sediment budget of the marsh under the dense (910 stems m^{-2}) *Spartina anglica* dominated plant canopy within the flume was not significantly altered despite a reduction in plant canopy height from an average of 10.7 cm to 1.3 cm. ~~Assuming that extrapolation through time is possible, our~~Our findings indicate that morphological changes to the saltmarsh canopy, such as those predicted with nutrient enrichment (Fox et al., 2012), grazing (Elschot et al., 2013; Nolte et al., 2013) or climate change (Reef et al., 2016) might not always have a significant impact on sediment deposition/erosion *in situ*.

Previous studies have compellingly shown that saltmarshes effectively attenuate tidal flows (Christiansen et al., 2000; Neumeier and Ciavola, 2004) and waves (Möller et al., 1999) as a function of vegetation density and height. However, potential linkages between vegetation canopy characteristics and small scale turbulence around plant elements (Widdows et al., 2008), mean that there is not necessarily a direct link between hydrodynamic conditions measured at the larger (metre) scale, sediment trapping, and sedimentation on the marsh surface. Attempts to link either vegetation parameters, or hydrodynamic measures alone, to sedimentation, are unlikely to succeed where the latter is explainable only through the interaction of the former two. Thus, Boorman et al. (1998) found no correlation between vegetation height and sediment accretion at one Essex saltmarsh, but did find a correlation at another marsh, suggesting that the relationship between vegetation structure and sedimentation can be site dependent. Despite flow attenuation, Widdows et al. (2008) even found enhanced erosion and lower sediment accretion rates in the lower sparsely vegetated saltmarsh due to enhancement of near bed turbulence relative to bare mud patches as the flow enters *Spartina anglica* canopies. In a North American saltmarsh, Moskalski and Sommerfield (2012) show that deposition and sediment trapping efficiency are not related to plant stem density but rather to the distance from the creek and suspended sediment properties. Studies on grazing by small and large herbivores on saltmarshes found a significant impact of grazing on vegetation height, but no subsequent effect on sediment deposition (Elschot et al., 2013). Similarly, our study indicates that contrary to theoretical predictions, during calm conditions the role of canopy morphology in areas where vegetation is present, is marginal for sediment accretion *in situ*. ~~This is perhaps due to the many other~~Our field based sampling design was such that it might not have been possible to detect a small effect of vegetation structure on deposition due to the dominance of the effects of hydrodynamic forcings and other, unmeasured interacting factors influencing sediment settling and erosion in this environment, such as microtopography (Stribling et al., 2007) and/or bed shear strength characteristics (Howes et al., 2010). Theoretical and lab based flume experiments provide optimal conditions for the detection of vegetation effects, even if they are small, by minimising the naturally occurring variability in other hydrodynamic and geomorphological factors, leading to a possible overestimation of the role of vegetation structure on sedimentation *in situ* under some conditions.

During the duration of our experiment, the missing impact of the vegetation-mediated sedimentation could have been caused by the typically calm summer weather conditions and the wave attenuating impacts of the flume. Significant wave heights in the flume averaged 0.02 m (derived from the wave proxy, Table 2), which is ten times lower than the mean wave heights measured at the saltmarsh pioneer zone at this location over a ten-month period (Möller and Spencer, 2002). The long term climate record for East Anglia wind speeds shows the lowest wind speeds occur in July, and that the wind speeds measured during the experimental period (daily average of 10 to 21 km h^{-1}) are within the range of the long term average for this month. The calm conditions generated low vertical mixing of the water column and led to low vertical mixing of suspended sediments. This resulted in suspended sediment travelling primarily within the lower 5 cm of the water column. The removal of sediment from the flume during ebb flow indicates that there is a highly mobile sediment fraction which is resuspended after initial sedimentation (during flood flow). Our sediment profiler data indicates that this sediment fraction travelled very close to the marsh surface (below 5 cm above the marsh surface, Figure 6). Only the final vegetation cover cutting reduced the mean vegetation height to within this height. Therefore, the imposed changes in vegetation morphology are not likely to have influenced this peak suspended sediment fraction.

Estimated flow speeds in the flume were very low, with maximum rising and falling velocities of less than 1 cm s^{-1}, characteristic of saltmarshes (e.g. Christiansen et al., 2000). Despite removing most of the plant canopy within the flume, surface roughness following the final vegetation cut was still noticeably greater than that of an unvegetated mudflat. Thus it is likely that the turbulent energy and flow structure close to the bed, remained similar following the vegetation cuts. Previous studies have suggested that sediment deposition is more strongly linked with marsh topography rather than with vegetation structure (Coulombier et al., 2012), and it could be that locally more sheltered areas associated with variations in topography caused by belowground vegetation structures trigger sedimentation of the suspended sediment. Our study also supports previous findings (van Eerdt, 1985) that belowground biomass (which remained mostly intact following the aboveground biomass removal) plays an important role in increasing bed-shear strength and preventing erosion (as the cutting of the vegetation canopy in our experiment did not significantly affect sediment loss from the flume during the ebb part of the tidal cycle). In this context, a large scale flume study showed that significant wave dissipation still occurs even when the aboveground biomass of a saltmarsh platform is mowed (Möller et al., 2014).

The net sediment gain per tide was on average only 13 % of the sediment flux entering the flume (Fig. 4). Thus the trapping efficiency of the tidally advected material was significantly lower than the hypothetical maximum and lower than simulations of sediment trapping efficiency in East Anglian marshes, using the numerical mass-balance model MARSH-0D, which predict trapping efficiencies of ca. 50% (French, 2006). Our calculated positive sediment budget of 12 g m^{-2} day^{-1} roughly compares to a vertical accretion rate of 2.7 mm y^{-1} (bulk density of $\rho = 1.6$ g cm^{-3} was measured for this site, R Reef unpublished data). Long term accretion rates measured using surface elevation tables and marker horizons adjacent to the flume show a net accretion of 7.3 mm y^{-1} (T Spencer, unpublished data). The accretion rates we measured during calm summer days are lower than the long-term average, supporting previous findings that accretion can be seasonal (Spencer et al., 2012), with higher rates during the more energetic winter season, a period when sediment supply is also higher (Prandle et al., 1997). High rates of accretion can also occur during infrequent high energy events (Stumpf, 1983; Schuerch et al., 2013). Our comparison of sediment budgets calculated using filter trap data with those calculated using the sediment mass balance approach suggest that the widely-used filter trap method could overestimate accretion, due to a lower erosion rate from the filter than from the surrounding sediments and/or the sediment removal occurred from surfaces other than those represented by the filter paper.

In conclusion, our findings suggest that during calm summer conditions the rate of sediment trapping by saltmarshes is independent of vegetation height or biomass. This is most likely due to very weak vertical mixing of sediment in the water column during calm sea conditions and the high surface roughness and bed-shear stress due to below ground plant structures. Our conclusion provides support for the simplification of vegetation canopies in numerical models of surface accretion under some hydrodynamic conditions. However, during periods of higher wind/wave energy and stronger vertical mixing of suspended sediments, the role of canopy structure could prove significant.

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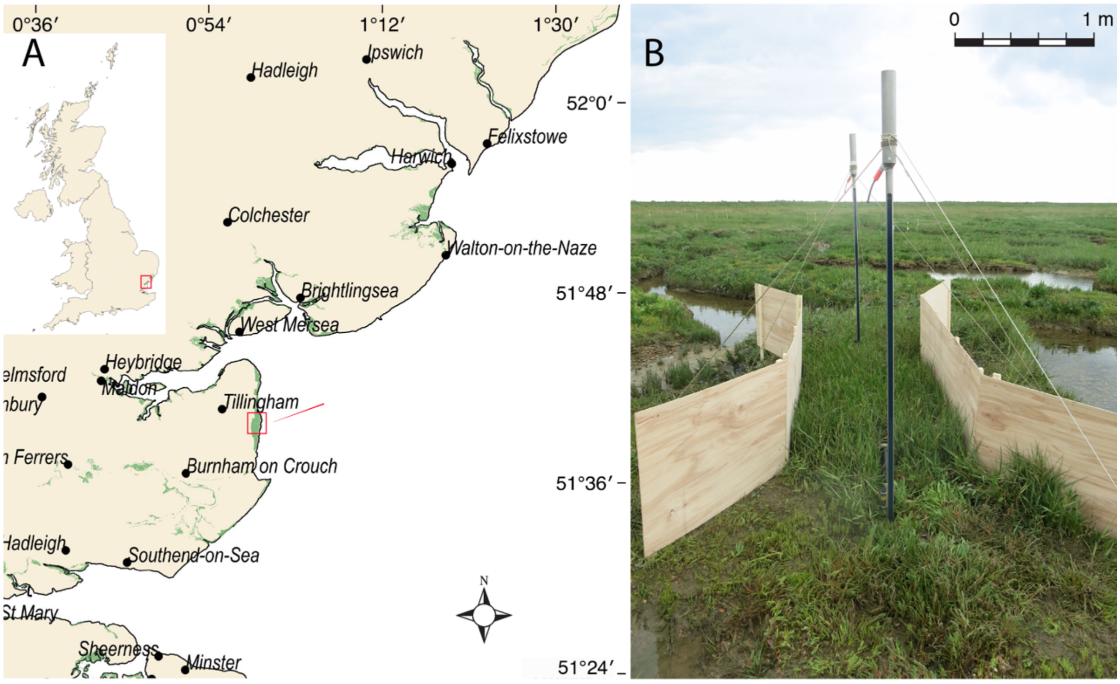
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Walton-on-the-Naze
Brightlingsea
West Mersea
Heybridge
Maldon
Tillingham
Burnham on Crouch
Southend-on-Sea
Sheerness
Minster
St Mary
N

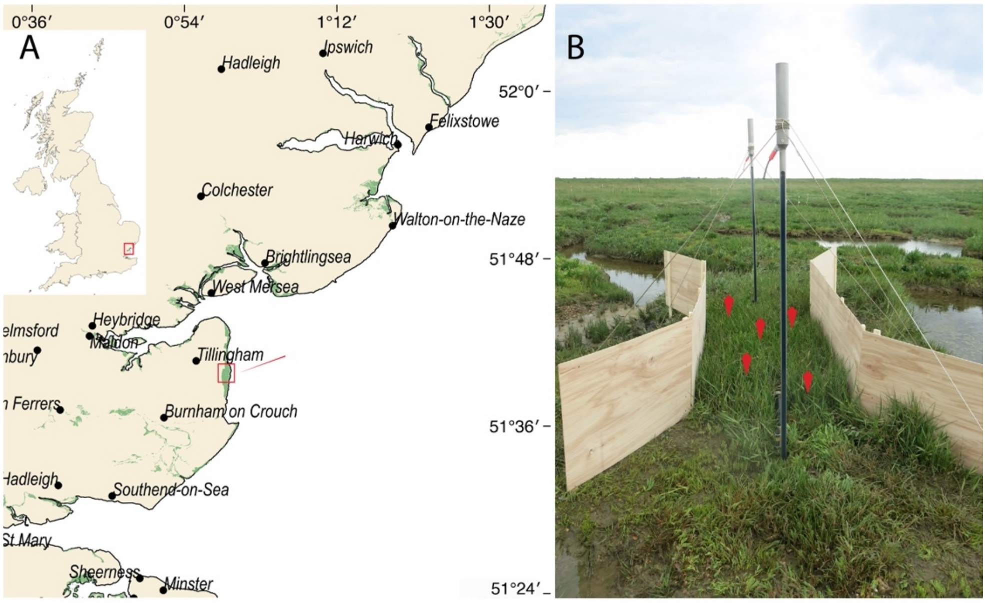
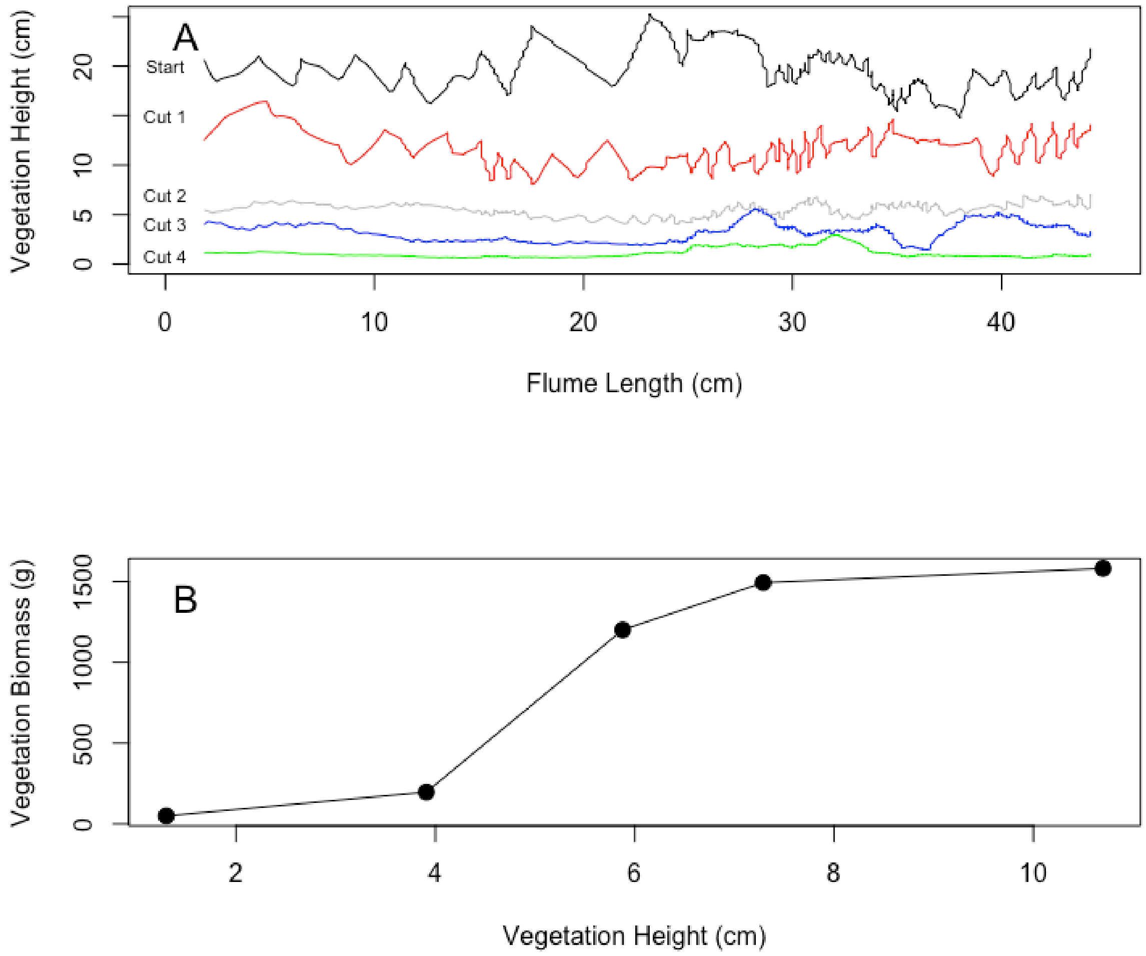


Figure 1: (a) The location of the study site near Tillingham, Essex, UK (51.69425°N 0.94206°E). Green shaded areas are saltmarshes. (b) a west-facing photo of the field flume, with the two ASM turbidity profilers and pressure sensors at the flume openings (~~scale bar refers to approximate left-to-right scale in front of image).~~the distance between the two ASM turbidity profilers was 1.82 m). Red markers point to the positions of the filters.



A
Start
Cut 1
Cut 2
Cut 3
Cut 4
Vegetation Height (cm)
Flume Length (cm)
0
5
10
20
0
10
20
30
40
B
Vegetation Biomass (g)
Vegetation Height (cm)
0
500
1000
1500
2
4
6
8
10

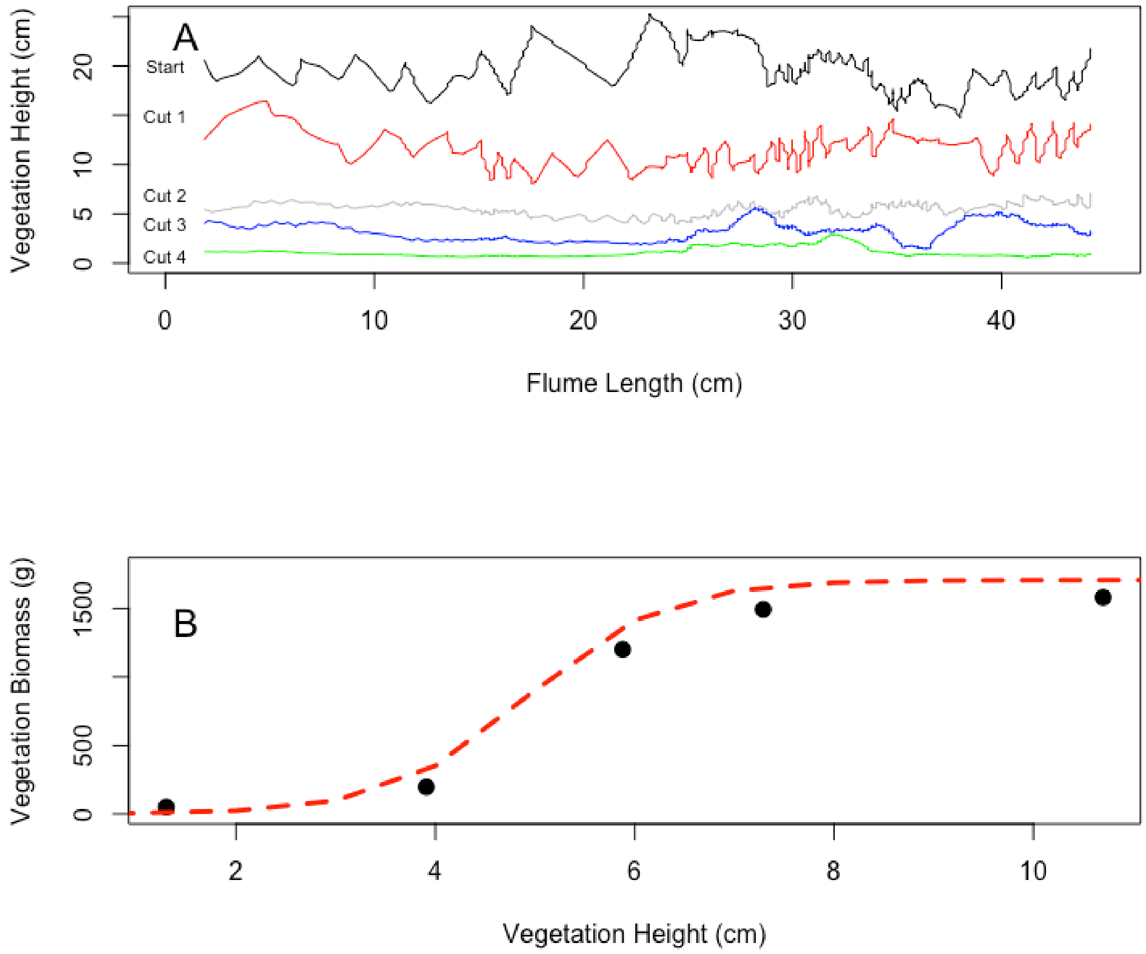
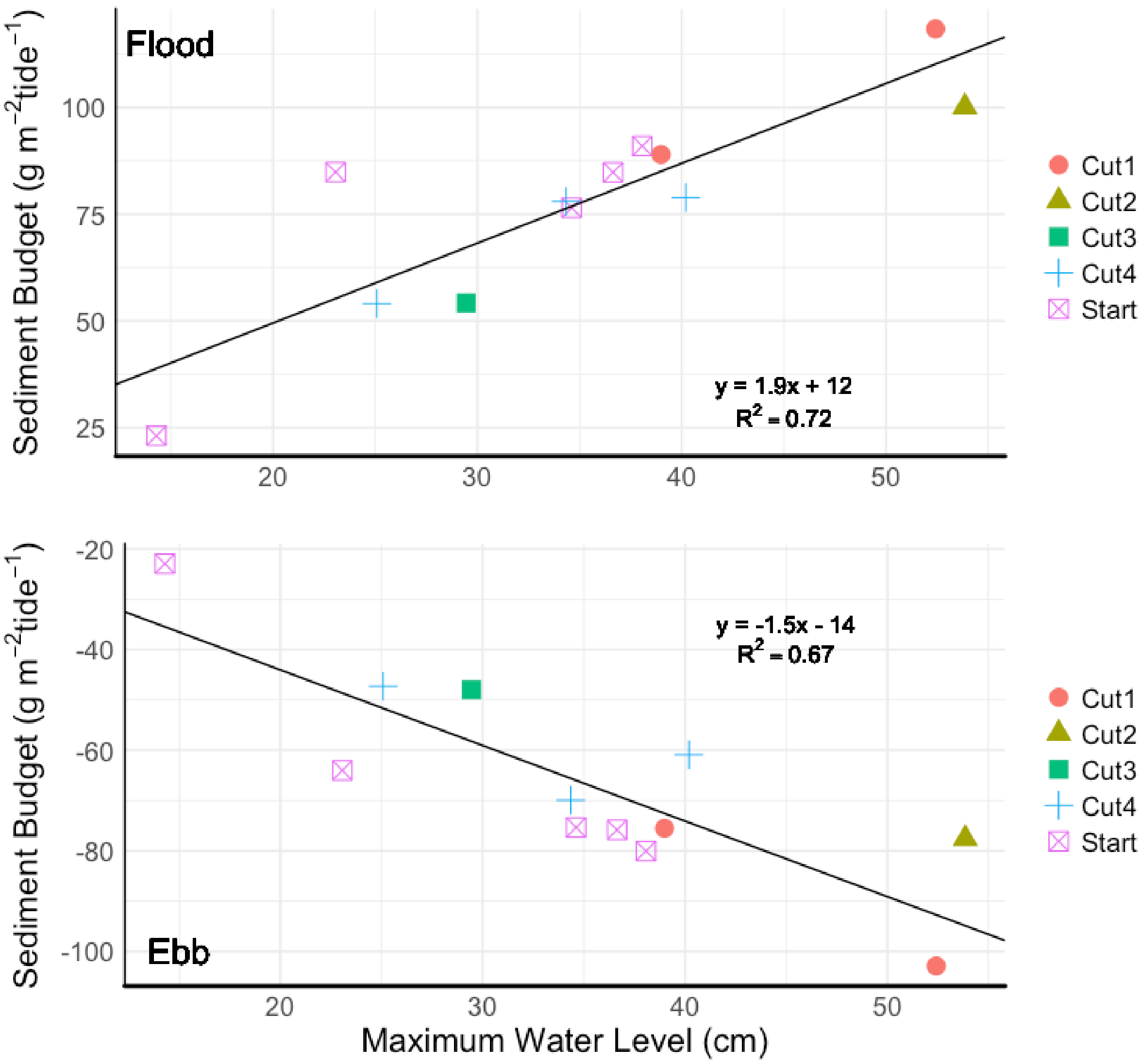


Figure 2: (a) A representative smoothed vegetation height profile along a section of the flume length for the initial conditions (Start) and subsequent vegetation cuts. The saltmarsh community within the flume was dominated by *Spartina alterniflora*, with an average stem density of 910 stems m^{-2} (b) the relationship between vegetation ~~height and biomass.~~biomass and height is depicted by the logistic population growth function:



$$Biomass = \frac{2150 \times e^{1.46 \times Height}}{1707 + 1.26\left(e^{1.46 \times Height} - 1\right)}$$

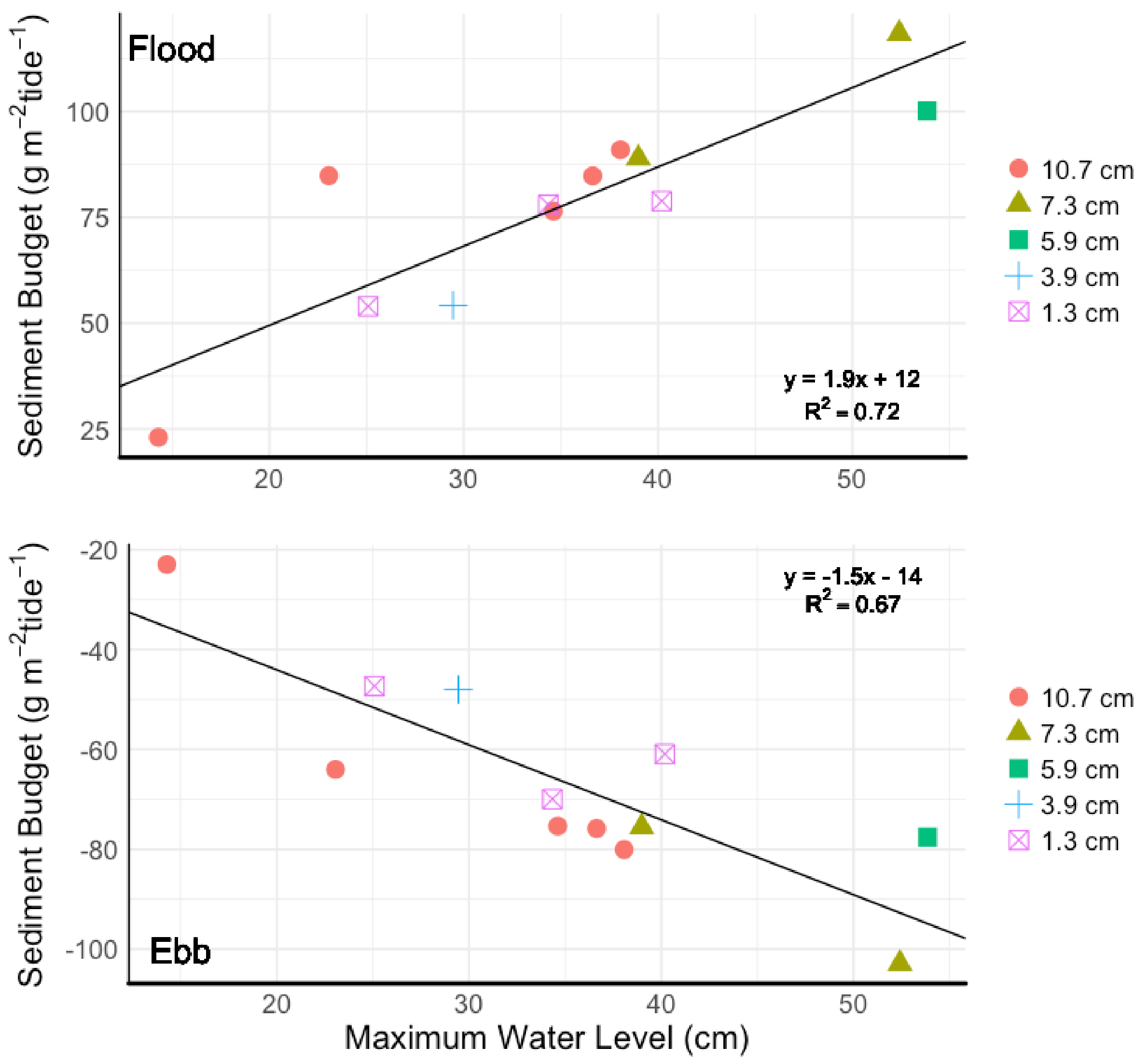


Figure 3: The sediment budget within the flume, calculated from the suspended sediment discharge between the upstream and downstream ASM sensors and the volume of water in the flume during the tidal period, as a function of maximum inundation ~~height~~depth (maximum water level during the tide) during the (a) flood and (b) ebb periods. Symbol shapes/colours correspond to different vegetation heights~~ ('start' and subsequent cutting events).~~. A linear regression model was fitted to the data and the equation and fit are presented in the panels.

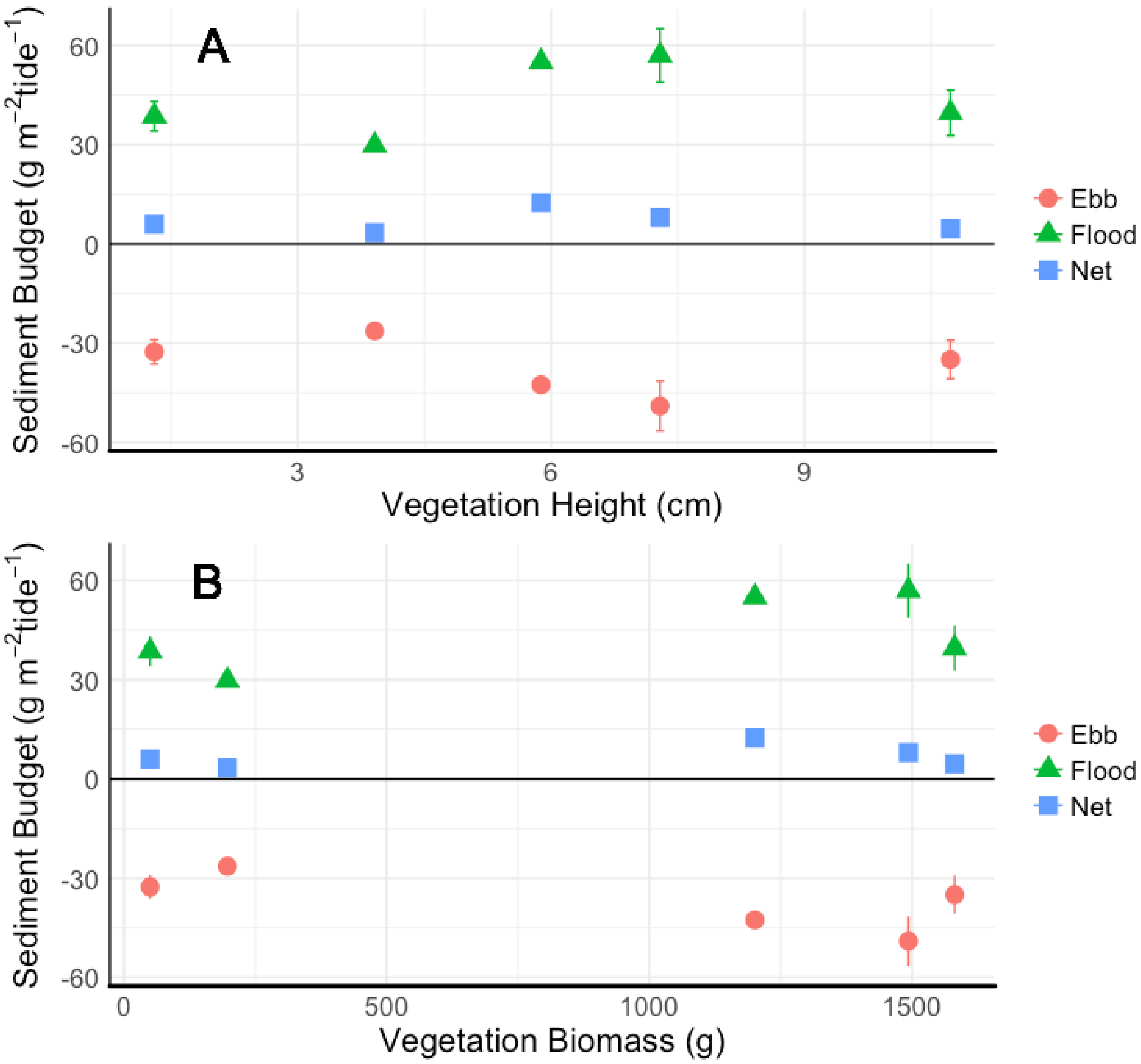
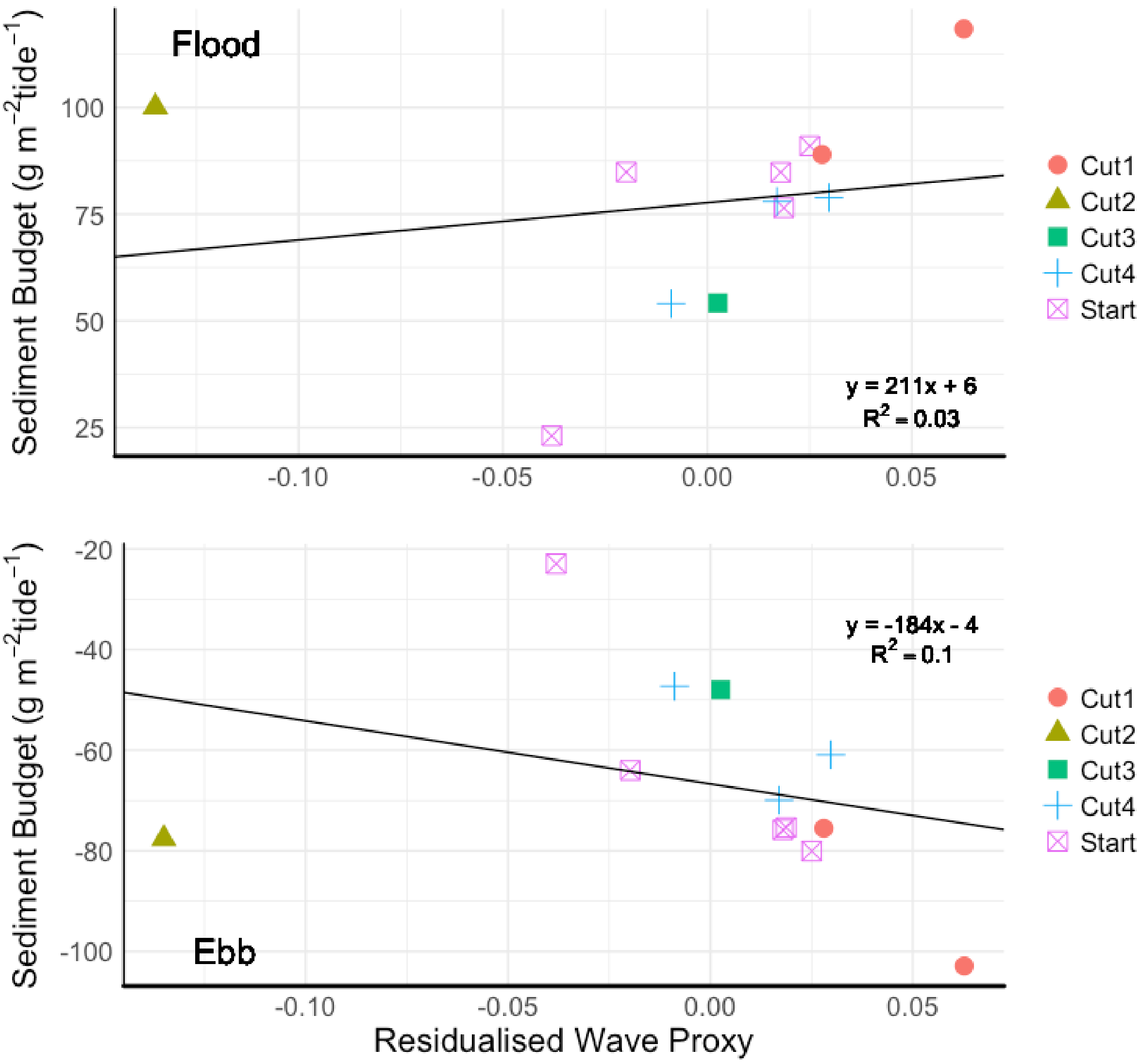


Figure 4: The mean (±SE) sediment budget within the flume, calculated from the difference in the depth-integrated suspended sediment concentration between the upstream and downstream ASM sensors (sediment discharge) and the volume of the water in the flume during the tidal period, as a function of (a) mean vegetation height and (b) vegetation biomass during the flood (green triangles) and ebb (red circles) periods. Blue squares are the mean sediment balance (±SE), with positive values indicating net sediment gain within the flume area and negative values, indicating net sediment loss from the flume area.



Flood
Sediment Budget (g m^{-2}tide^{-1})
100
75
50
25
-0.10
-0.05
0.00
0.05
y = 211x + 6
R^2 = 0.03
Cut1
Cut2
Cut3
Cut4
Start
Ebb
Sediment Budget (g m^{-2}tide^{-1})
-20
-40
-60
-80
-100
y = -184x - 4
R^2 = 0.1
Residualised Wave Proxy

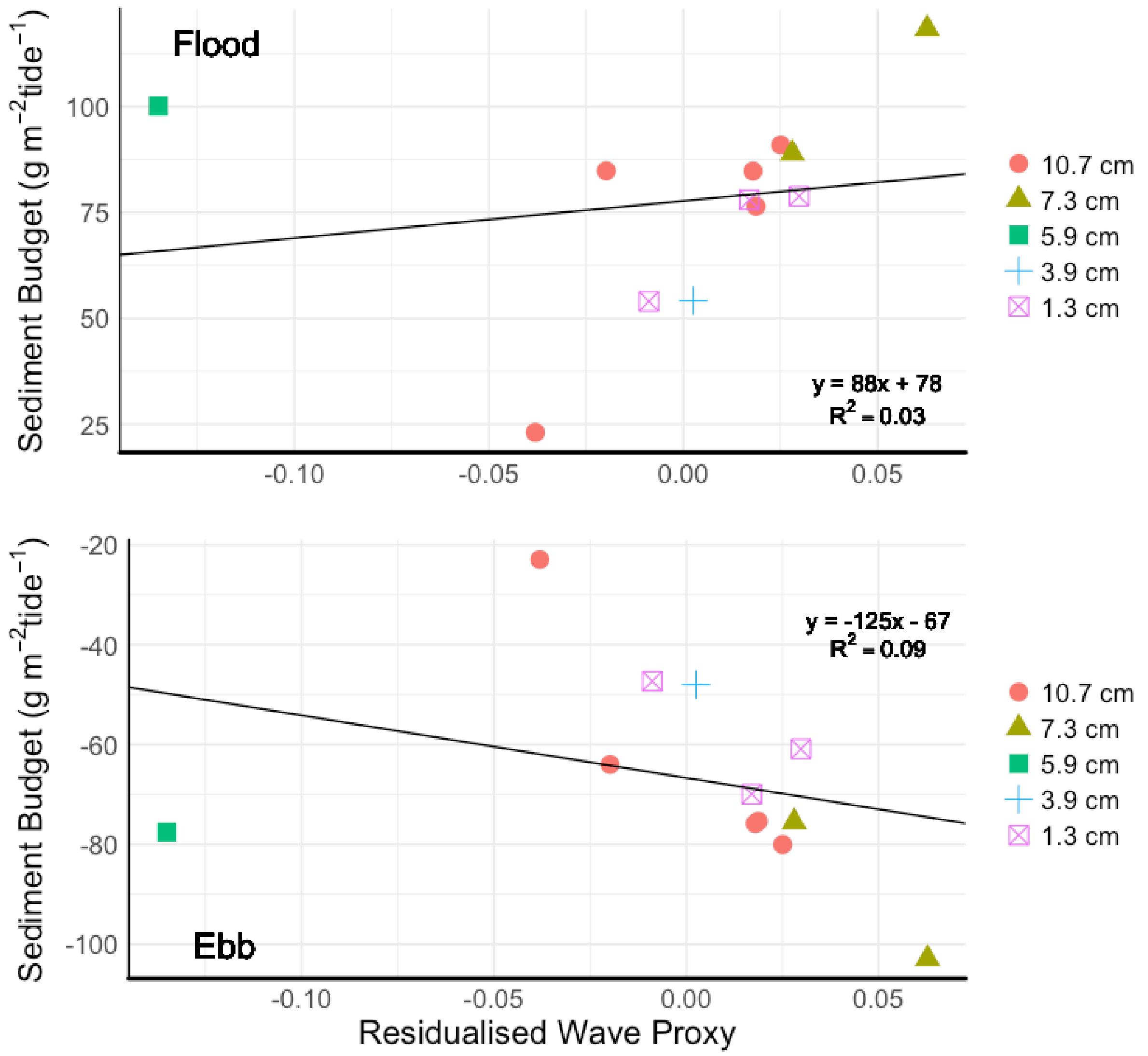


Figure 5: The effect of the residualised predictor wave proxy (corrected for the influence of maximum water level) on the sediment budget within the flume, calculated from the difference in suspended sediment concentration between the upstream and downstream ASM sensors (sediment discharge) and the volume of water in the flume during the tidal period, as a function of the wave proxy during the (a) flood and (b) ebb periods. Symbol shapes/colours correspond to different vegetation heights ~~('start' and subsequent cutting events).~~. A linear regression model was fitted to the data and the equation and fit are presented in the panels.

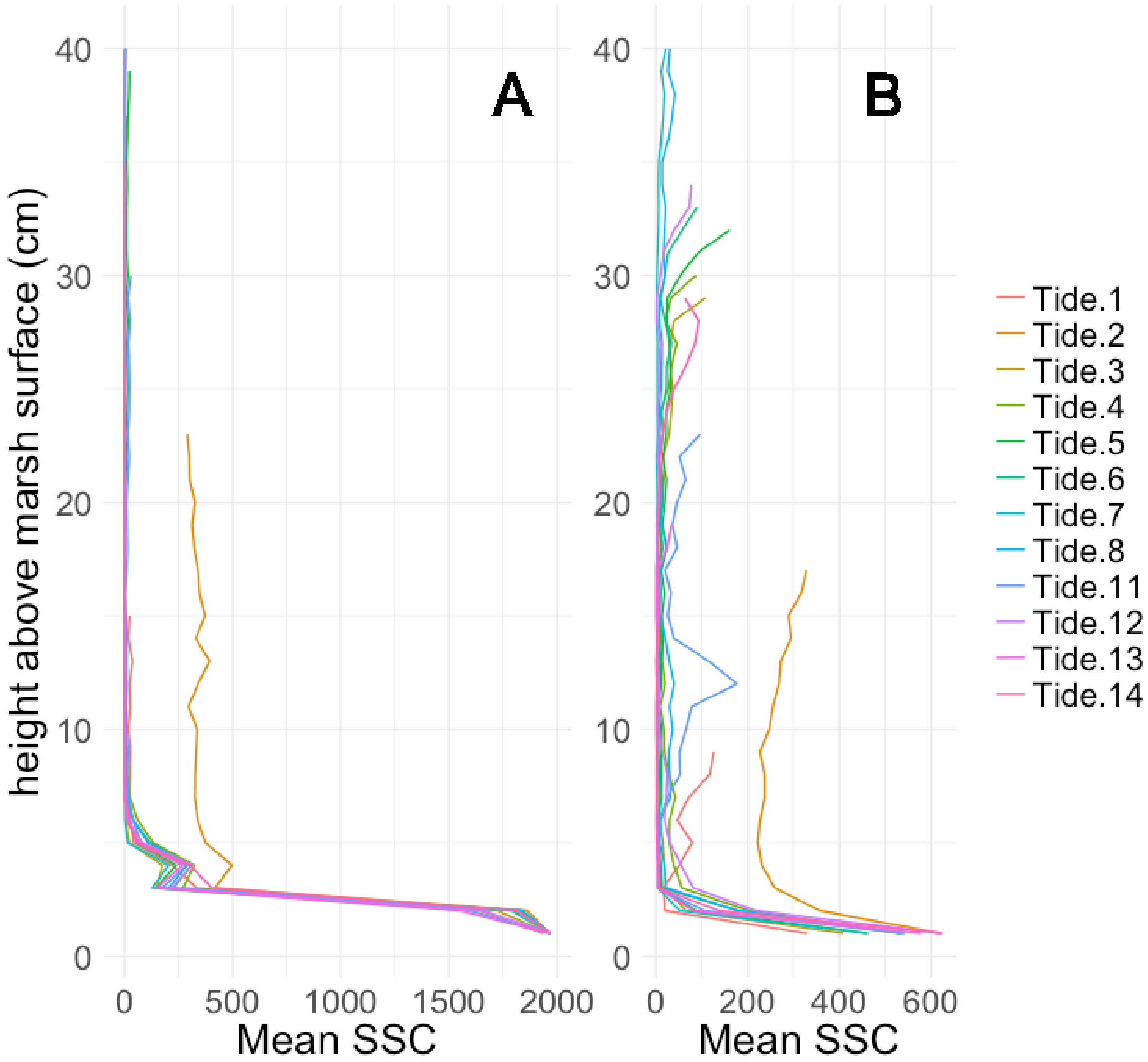


Figure 6: Suspended sediment concentrations (g m^{-3}) measured at different heights above the marsh surface at 1 cm intervals at the (a) seaward and (b) landward openings of the flume. Suspended sediment concentrations were much higher closer to the marsh surface (below 5 cm). Each line represents the mean for an entire inundation period for each sensor. The hydrodynamic conditions of each tide are described in Table 1.

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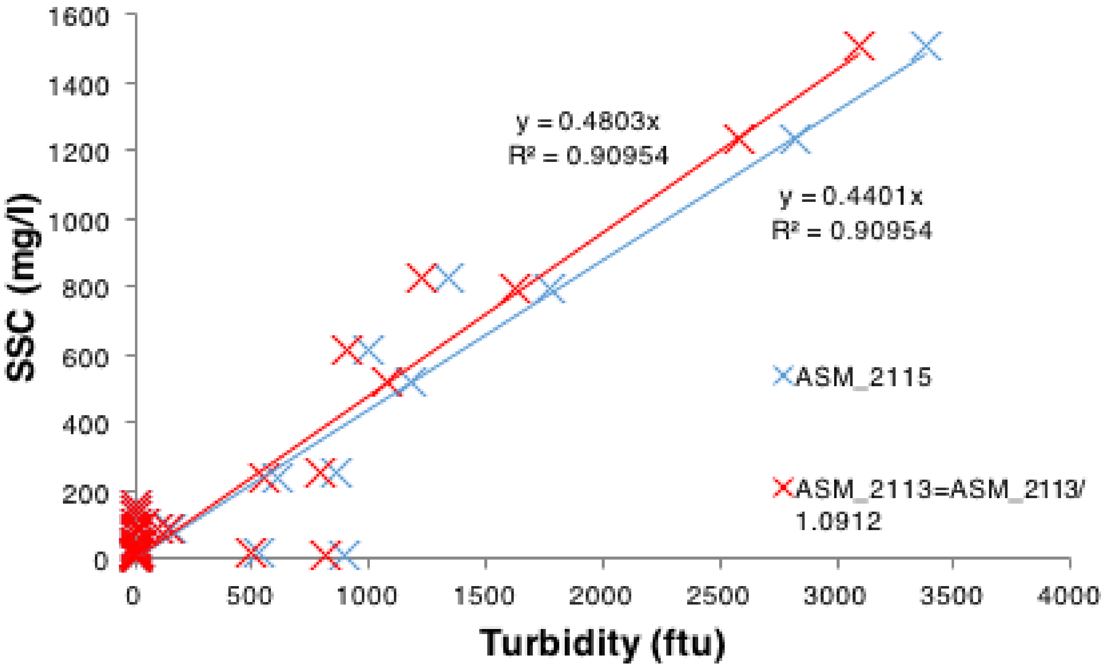
Figure S1: Calibration curves for the two ASM turbidity profilers used in the flume study. The 24 points of calibration were collected over a four-day period, immediately proceeding the flume experiment. Turbidity, measured by the ASM sensors, 4 cm above the marsh surface, was compared with sediment dry mass in 1 L water samples collected at the same time and from the same depth, using an ISCO automated water sampler and filtered on a GF/F filter. Both ASM sensors and the water sampler intake hose were placed together during the calibration period.



The effect of vegetation height and biomass on the sediment budget of a European saltmarsh

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Keywords:
Erosion, deposition, Spartina, trapping efficiency, flume, inundation

Abstract

Sediment retention in saltmarshes is often attributed to the presence of vegetation, which enhances accretion by slowing water flow, reduces erosion by attenuating wave energy and increases surface stability through the presence of organic matter. Saltmarsh vegetation morphology varies considerably on a range of spatial and temporal scales, but the effect of different above ground morphologies on sediment retention is not well characterised. Understanding the biophysical interaction between the canopy and sediment trapping *in situ* is important for improving numerical shoreline models. In a novel field flume study, we measured the effect of vegetation height and biomass on sediment trapping using a mass balance approach. Suspended sediment profilers were placed at both openings of a field flume built across-shore on the seaward boundary of an intertidal saltmarsh in the Dengie Peninsula, UK. Sequential removal of plant material from within the flume resulted in incremental loss of vegetation height and biomass. The difference between the concentration of suspended sediment measured at each profiler was used to determine the sediment budget within the flume. Deposition of material on the plant/soil surfaces within the flume occurred during flood tides, while ebb flow resulted in erosion (to a lesser degree) from the flume area, with a positive sediment budget of on average 6.5 g m^{-2} $tide^{-1}$ with no significant relationship between sediment trapping efficiency and canopy morphology. Deposition (and erosion) rates were positively correlated to maximum inundation depth. Our results suggest that during periods of calm conditions, changes to canopy morphology do not result in significant changes in sediment budgets in marshes.

Introduction

The balance between sea level rise and rates of sediment accretion is a key research question in the broader debate as to whether or not marsh surfaces will be able to keep up with near-future accelerated sea level rise (Orson et al., 1985; Kirwan et al., 2010). Sea level rise poses a threat to intertidal saltmarshes due to seawater inundation beyond the physiological tolerance of the vegetation. However, the ability of marshes to accrete vertically through sediment trapping and root growth allows them to maintain their position in the tidal frame as it is translated upwards, promoting their long-term stability and survival (Morris et al., 2002; French, 2006; McIvor et al., 2013). It has been argued that the presence of vegetation enhances sedimentation on saltmarsh platforms both by attenuating wave energy and slowing water flow (Boorman et al., 1998; Temmerman et al., 2005) and by preventing the resuspension of deposited sediments on, and the direct erosion of, saltmarsh surfaces (Fagherazzi et al., 2012).

The presence or absence of vegetation, as well as vegetation parameters such as height and biomass are thought to be key factors in determining rates and patterns of sediment trapping and deposition, although this relationship is non-linear (Nardin and Edmonds, 2014) and may be dependent on wave and flow conditions. The importance of vegetation structure in marsh functioning is well recognised but its incorporation in realistic representations of the interactions between vegetation and sedimentation is complicated by the immense variability in canopy structure on a range of scales. Marsh vegetation shows great inter-specific variability in stem flexibility (Tempest et al., 2015; Rupprecht et al., 2017) affecting plant-flow interactions and sedimentation. Furthermore, marsh vegetation is regularly subjected to both emergent and submerged states and, in the case of the latter, to both 'normal' and extreme 'storm surge' flow regimes. Vegetation height and biomass varies both spatially and temporally on European saltmarshes. Such canopy characteristics vary with intertidal elevation (Silvestri et al., 2005) and with the seasons. Communities are typically composed of a combination of perennial and annual species with little above ground presence during winter (Watkinson and Davy, 1985) when annual species are absent and perennial saltmarsh species biomass is also much reduced (Hussey and Long, 1982; De Leeuw et al., 1990). Biomass reaches a peak at the end of the northern summer growing season (De Leeuw et al., 1990). In the longer term, saltmarsh canopy height and biomass vary as a function of climate change (Arp et al., 1993; Reef et al., 2016) and eutrophication (Deegan et al., 2007).

While slower flow rates in vegetated areas enhance particle settlements and thus deposition (Neumeier and Amos, 2006), the movements of plants when acted on by waves and currents can scour the surface and significantly enhance erosion, particularly in the pioneer zone and along marsh seaward margins (Temmerman et al., 2007; Feagin et al., 2009). Sheehan and Ellison (2015) observed significantly lower accretion and higher erosion rates immediately following the complete removal of a saltmarsh vegetation cover, although the addition of organic matter to the soil substrate over time contributes to erosion-resistant soils (Feagin et al., 2009). Periods of increased erosion in UK saltmarshes coincide with periods of higher winds and wave heights (van der Wal and Pye, 2004; Wolters et al., 2005); this may also cause increased sedimentation on the saltmarsh platform (Schuerch et al., 2012). There are, however, relatively few studies worldwide on the efficiency with which saltmarshes trap tidally advected material in field conditions (French, 2006; Moskalski and Sommerfield, 2012; Spencer et al., 2015b; van der Deijl et al., 2017). In this study, we aim to close this knowledge gap of the role of vegetation structure on deposition *in situ* through the use of a field flume, in combination with a mass balance approach to determine how changes to canopy morphology affect trapping efficiency in a UK saltmarsh.

Methods

Setting and physical environment

The field study was undertaken on the UK east coast at Tillingham, Dengie Peninsula, (51.69425°N 0.94206°E, Fig. 1A) between the estuaries of the Rivers Blackwater and Crouch. The saltmarsh is a near-horizontal platform of clayey silts, ca. 200 m in width, at an elevation of 1.9 - 2.5 m above Ordnance Datum Newlyn (ODN; where 0.0 ODN approximates to mean sea level). The tidal mudflat immediately seaward of the marshes are at elevations of 0.9 - 1.9 m ODN and show a 'mudmound topography' of shore-normal sinuous ridges and runnels in the transition zone between the saltmarsh and the flat tidal mudflat. The runnels narrow shorewards into small creeks which dissect the marsh surface (Möller and Spencer, 2002). The Dengie Peninsula coast is macrotidal, with a mean spring tidal range of 4.8 m (Reed, 1988). The southern North Sea is, however, particularly susceptible to storm surges which raise water levels well above expected tidal levels. Thus the storm surges of 1953 and 2013 reached 4.4 m ODN at West Mersea, Blackwater estuary (Spencer et al., 2015a), resulting in water depths of ca. 2 m over marsh surfaces. The wave climate is moderate with a maximum recorded significant wave height (H_s) of 0.65 m at Sales Point on the northern limit of the Peninsula (Herman, 1999).

The main sediment sources for the marshes in East Anglia are thought to be the erosion of coastal cliffs in Norfolk and Suffolk, and to a much lesser extent, fluvial inputs from East Anglian rivers, and offshore seabed erosion (McCave, 1987). The cliff sediments are unconsolidated Quaternary sediments with a high proportion of inorganic mud. Suspended sediment concentrations in the southern North Sea are highly seasonal, with more than a fourfold increase in sediment concentrations in winter compared to summer (Prandle et al., 1997). Our experiment was undertaken during summer, when sediment supply to the marsh is lowest, but vegetation biomass is highest.

Experimental design

The experiment was carried out during the spring tide period between the 2-9 July 2016. We selected an area towards the seaward fringe of the saltmarsh at Tillingham and enclosed it within a plywood flume channel secured to the marsh surface with wooden stakes. The flume was 1000 mm in width, 1820 mm in length and the vertical walls were 900 mm high, with symmetrical funnel shaped openings at each end (Fig. 1B). It was placed across-shore (E-W), corresponding to the main direction of tidal flow. One profiling turbidity sensor (Argus Surface Meter (ASM) IV) and one pressure sensor (Solnist Levellogger Edge, Model 3001) were placed in the centre of both openings. The ASM IV turbidity profilers are titanium rods consisting of a series of 144 optical backscatter (OBS) sensors arranged as an array, with a 10 mm vertical spacing. The profilers and pressure sensors were programmed to record a depth-averaged turbidity profile (10 measurements over 10 s) and a water depth every 30 seconds

Hydrodynamic measurements

The hydrodynamic conditions during the experiment were primarily deduced from the water levels recorded by the pressure sensors. The continuous (or still) water levels and the maximum tidal inundation depth were derived from a smoothed water level curve, which was calculated using a moving-average filter with a window size of 15 minutes (=30 data records). A proxy for wave heights was calculated for every tidal inundation as the standard deviation of the differences between the recorded and the still water level (smoothed water level curve) and validated with actual wave measurements, using a PTX1830 pressure transmitter (Möller, 2006) during a previous measurement campaign. Validation of the wave proxy resulted in a highly significant correlation between the wave proxy calculated from the smoothed water curve and the measured wave heights measured using the PTX1830 of the form (*wave height (cm)* =6.465 x *wave proxy*, R^2=0.92, $p<0.001$). Wind conditions were obtained from two UK Met Office coastal meteorological stations in Essex, one at Walton-on-Naze and one at Shoeburyness (Southend-on-Sea). Average daily wind speeds (measured at Walton-on-Naze, Essex and at Shoeburryness, Essex) ranged between 10 and 21 km h^{-1} with a predominant W/SW direction (UK Met Office, www.metoffice.gov.uk).

Sediment budget measurements

In order to calibrate the ASM sensor turbidity readings to g m^{-3}, water samples (1 L) were collected at 4 cm above the marsh surface using an automated water sampler (ISCO 6712, Teledyne Isco, Lincoln NE, USA) in the pioneer zone of the saltmarsh during two spring tide periods in April (7-11 April 2016) and July (21-24 July 2016). In each calibration period, three samples were taken, 30 minutes apart, during each inundation over eight consecutive inundations (N=24). Following collection, the samples were filtered through pre-weighed GF/C filters, which were then dried at 105°C for 24 hours and re-weighed. Measured sediment concentrations in the water samples were compared to the simultaneously measured turbidity levels recorded by both ASM IV at 4 cm above the marsh surface. A calibration curve was derived for each of the devices, relating turbidity to suspended sediment concentrations (SSC) (R^2=0.91, Fig. S1).

A sediment budget for each tidal stage (flood and ebb phase) was calculated by numerical integration of the depth-averaged SSC difference between the upstream and downstream ASM sensors (g m^{-3}) over the instantaneous volume within the flume (m^3), using the trapezoidal rule. From the two ASM sensors at each end of the flume, the upstream and downstream sensors were assigned based on the tidal stage (i.e. the seaward sensor was assigned as the upstream sensor during the flood tide and as the downstream sensor during the ebb tide). Due to negligible flow velocities during slack water, we excluded the data from the slack tide period from our analysis. Slack tide was defined as the period where the rate of change of the smoothed water depth curve was $<3.3\text{x}10^{-3}$ cm s^{-1}. Furthermore, data from water depths of <3 cm within the flume were excluded because of increasing relative measurement errors for small water depths.

A positive sediment budget denoted sediment deposition within the flume, whereas a negative value indicated erosion. The sediment budget was defined as the amount of sediment that was actually retained within the flume over the tidal cycle. Assuming an insignificant change in the amount of material held on plant surfaces, this should closely match the deposition data recorded by the GF/C filters deployed on the bed within the flume (see below).

Vegetation canopy height and biomass manipulation

The vegetation within the flume consisted of a typical '*Spartina alterniflora* saltmarsh community' (British NVC, SM5) dominated by *Spartina alterniflora* (50 % cover), *Aster tripolium* (17 % cover) and *Puccinellia maritima* (10 % cover) with some individuals of annual *Salicornia* spp. (5 %), *Suaeda maritima* (3 %) and *Atriplex portulacoides* (1 %). Vegetation ground cover in the flume was 86 %. Initial vegetation height within the flume was on average (± SD) 10.7 cm (± 2.2) with a maximum height of 26.7 cm (± 3.4) (Fig. 2). The 75th percentile was on average 15 cm (± 2.7). Average stem density was 910 stems m^{-2} (± 240) within the flume.

In order to quantify the effect of plant canopy morphology on the saltmarsh sediment budget, we reduced the height of the vegetation in the flume by ca. 5 cm every other inundation (Fig. 2A). The cut material was collected, dried (48 hours at 105°C) and weighed for biomass determination (Fig. 2B). Four cuts were carried out, reducing the mean canopy height from 10.7 cm (range 0-27 cm) to a final mean height of 1.3 cm (range 0-5.4 cm). Canopy height was measured across the entire flume area, using eight, scale calibrated, side-on photographs (Rupprecht et al., 2015) and analysed using line graph analysis (Image J, Schneider et al., 2012). The canopy (green) was easily distinguished digitally from the flume wall background (light tan) using a grey scale threshold. A digitised line plot was then created from the threshold edge so that the y-axis was height above bottom in cm and the x axis was cm from flume opening along the ground. Vegetation stem density was measured by manually counting stems in five 20 cm x 20 cm quadrats within the flume.

Measuring sediment deposition

Five glass petri dishes, inserted level with the soil surface, were evenly distributed within the flume (Fig. 1B). Pre-weighed glass fibre (GF/C) papers (9 cm diameter) were placed on the surface of each petri dish and held in position with small metal pins. The filters were exchanged every other tidal inundation and the dry weight of sediment deposited on the filters was measured after drying at 105°C for 24 hours.

The sediment characteristics (grain size and organic carbon content) were determined using hardened ashless filter papers (Whatman, Grade 540) distributed on the marsh, as above, during the 4-day July calibration period. The filters were then dried at 105°C for 24 hours and weighed, before being combusted at 505°C for 6 hours to burn away the filter paper and to determine sediment loss-on-ignition. The remaining sediment was weighed to determine the loss-on-ignition, representing the organic carbon content and analysed for grain size, using a Malvern Mastersizer 2000.

Statistical analysis

The relationship between vegetation height or biomass and deposition was measured using multiple linear regression with vegetation height (or biomass) and the hydrodynamic variable, maximum water level, as the predictors and deposition as the dependent variable. The two co-variates, maximum water level and vegetation height were not linearly correlated (p=0.65), satisfying the assumption of independence. To measure the effect of waves on deposition, we used a multiple regression model with wave proxy and vegetation height as predictors of deposition. Due to the collinearity of wave proxy and maximum water depth, we residualised wave proxy by running a preliminary regression analysis between wave proxy and maximum inundation depth and used the residuals from this analysis (wave proxy_{resid}) in lieu of wave proxy in the multiple regression model. For all linear models, the normality assumption was tested by the visual inspection of the histograms of the model residuals.

Results

Hydrodynamic and sediment characteristics

During the duration of the experiment (2-9 July 2016), we measured 14 tidal inundations over a set of rising and then falling spring tides, peaking on 7 July 2016 with a predicted high water level of 2.01 m (ODN) at Harwich, Essex, 40 km NE of the study site (Table 1). Mean High Water Springs (MHWS) at Harwich is 1.99 m ODN and Highest Astronomical Tide (HAT) is 2.44 m ODN. Due to flume damage on 6 July 2016, we had to remove tides 9 and 10 (6 and 7 July 2016) from the dataset.

Maximum inundation depths in the flume for each tidal inundation during the period of the experiment ranged from 0.14 m to 0.54 m (Table 1). The highest inundation depths were measured during tides 7 and 8 with 0.52 and 0.54 m respectively. With a maximum profiling range of 1.44 m, the observed inundations allowed for the capture of a complete turbidity profile during every tide.

The wave activity during the experiment, as represented by the wave proxy, was closely, positively correlated with the maximum inundation depth (r = 0.86), apart for tide 8. The highest wave proxy value occurred during tide 7 with the lowest values being observed during the first two tides (Table 1).

Depth-integrated tidal horizontal velocities within the flume were approximated by the rate of change in water depth between measurements (rising velocity). On average the peak rising velocity during flood tides was 0.64 cm s^{-1}, whereas the average peak rising velocity during ebb tides was -0.57 cm s^{-1} (Table 1). The absolute highest rising velocity recorded was 0.90 cm s^{-1} during the flood of tide 8. During most of the observed tides the maximum rising velocity during flood tides was higher than during ebb tides (flood : ebb ratio >1) indicating a flood dominant inundation regime (Table 1). The most pronounced flood dominance was observed during tide 6, whereas tides 2 and 13 were the only tides showing ebb dominance (flood : ebb ratio < 1).

The sediment that settled on the filters in the flume during the calibration period was primarily composed of very fine sand (D_{50} = 121.9 µm, skewness = -0.19) and contained, on average (±SD), 15.4 % ±4.9 % organic matter.

Table 1: Hydrodynamic characteristics of the different flume inundation periods during the experiment.

Tide	Vegetation Height (m)	Vegetation Cut	Maximum Inundation Depth (m)	Max Flood Velocity* (cm s^{-1})	Max Ebb Velocity* (cm s^{-1})	Flood/Ebb Ratio	Wave proxy
1	0.107	Start	0.143	0.338	0.322	1.049	0.149
2	0.107	Start	0.231	0.470	0.473	0.993	0.232
3	0.107	Start	0.346	0.614	0.587	1.046	0.355
4	0.107	Start	0.366	0.677	0.579	1.169	0.369
5	0.107	Start	0.381	0.684	0.563	1.215	0.386
6	0.073	Cut 1	0.390	0.743	0.608	1.222	0.396
7	0.073	Cut 1	0.524	0.848	0.742	1.143	0.529
8	0.059	Cut 2	0.539	0.916	0.753	1.215	0.342
11	0.039	Cut 3	0.294	0.641	0.542	1.182	0.300
12	0.013	Cut 4	0.402	0.698	0.601	1.161	0.406
13	0.013	Cut 4	0.251	0.461	0.491	0.940	0.257
14	0.013	Cut 4	0.34	0.63	0.58	1.10	0.351

* Tidal horizontal velocities within the flume were approximated by the rate of change in water depth between measurements (rising velocity).

Sediment budget

The sediment budgets (deposition minus erosion of sediment) of the flood and the ebb periods for the flume area were both significantly affected by the maximum water level (multiple linear regression, β = 1.94, $p < 0.001$, R^2 = 0.74 and β = -1.57, $p < 0.001$, R^2 = 0.72 for flood and ebb periods respectively, Fig. 3), but not by the height of the vegetation. Vegetation height was not a significant factor for sediment budgets in either flood or ebb periods (β = 1.2, p = 0.22, R^2 = 0.74 and β = -1.35, p =0.12, R^2 = 0.72 respectively, Fig. 4A). Vegetation biomass, which showed a non-linear reduction in relation to vegetation height (Fig. 2B) was also found to have no significant effect on the sediment budget during flood and ebb flows (multiple linear regression, β = 0.007, p = 0.21, R^2 = 0.74 and β = -0.007, p = 0.14, R^2 = 0.72, respectively, Fig. 4B). The net sediment budget following a full inundation cycle was not affected by maximum inundation depth, vegetation height or vegetation biomass (β = 0.36, p = 0.07; β = -0.09, p = 0.85, R^2 = 0.19; β = -0.00007, p = 0.97, R^2 = 0.19; respectively).

The sediment budget within the flume following each stage of the tide (Fig. 4) indicated sediment import into the flume area during the flood period (42.7 ± 13.53 g m^{-2}), and export from the flume area during the ebb period (-36.6 ± 11.15 g m^{-2}). Import during the flood was consistently greater than export during the ebb periods throughout the measurement period. Hence, the net sediment budget per tide was on average positive (6.1 ± 3.98 g m^{-2}).

A multiple linear regression with the residualised wave proxy and vegetation height as predictors, found that the wave proxy was not a significant forcing on the sediment budgets during flooding (Fig. 5A, multiple linear regression, $\beta = 88.4$, $p = 0.60$, $R^2=0.03$) nor during ebb flows (Fig. 5B, $\beta = -126.3$, $p = 0.35$, $R^2 = 0.11$).

The amount of sediment deposited on the filter traps within the flume was not significantly affected by canopy height ($R^2 = 0.01$, $p = 0.79$). There was no correlation between the mass of the sediment deposited on the filter traps and the mass balance calculation of net sediment budgets within the flume (Pearson's r = 0.26), but a high correlation was observed between sediment trapping on the filter and sediment deposition within the flume during flood periods calculated using the mass balance approach (Pearson's r = 0.72).

Sediment concentrations were significantly higher closer to the marsh surface than higher in the water column (Fig. 6). The mean SSC in the bottom 5 cm was more than 10 times higher than that measured for the rest of the water column (t-test, $p<0.001$). This pattern was more pronounced for the seaward sensor (Fig. 6A) than for the landward sensor (Fig. 6B). For both sensors, only tide 2 showed the presence of suspended sediment within the middle and upper parts of the water column.

Discussion

Our field study indicates that under calm summer conditions, tidal flooding delivers very fine sand to the lower marsh at Tillingham, Essex, which is deposited at a rate that is not demonstrably affected by canopy height and biomass. The sediment budget of the marsh under the dense (910 stems m^{-2}) *Spartina anglica* dominated plant canopy within the flume was not significantly altered despite a reduction in plant canopy height from an average of 10.7 cm to 1.3 cm. Our findings indicate that morphological changes to the saltmarsh canopy, such as those predicted with nutrient enrichment (Fox et al., 2012), grazing (Elschot et al., 2013; Nolte et al., 2013) or climate change (Reef et al., 2016) might not always have a significant impact on sediment deposition/erosion *in situ*.

Previous studies have compellingly shown that saltmarshes effectively attenuate tidal flows (Christiansen et al., 2000; Neumeier and Ciavola, 2004) and waves (Möller et al., 1999) as a function of vegetation density and height. However, potential linkages between vegetation canopy characteristics and small scale turbulence around plant elements (Widdows et al., 2008), mean that there is not necessarily a direct link between hydrodynamic conditions measured at the larger (metre) scale, sediment trapping, and sedimentation on the marsh surface. Attempts to link either vegetation parameters, or hydrodynamic measures alone, to sedimentation, are unlikely to succeed where the latter is explainable only through the interaction of the former two. Thus, Boorman et al. (1998) found no correlation between vegetation height and sediment accretion at one Essex saltmarsh, but did find a correlation at another marsh, suggesting that the relationship between vegetation structure and sedimentation can be site dependent. Despite flow attenuation, Widdows et al. (2008) even found enhanced erosion and lower sediment accretion rates in the lower sparsely vegetated saltmarsh due to enhancement of near bed turbulence relative to bare mud patches as the flow enters *Spartina anglica* canopies. In a North American saltmarsh, Moskalski and Sommerfield (2012) show that deposition and sediment trapping efficiency are not related to plant stem density but rather to the distance from the creek and suspended sediment properties. Studies on grazing by small and large herbivores on saltmarshes found a significant impact of grazing on vegetation height, but no subsequent effect on sediment deposition (Elschot et al., 2013). Similarly, our study indicates that contrary to theoretical predictions, during calm conditions the role of canopy morphology in areas where vegetation is present, is marginal for sediment accretion *in situ*. Our field based sampling design was such that it might not have been possible to detect a small effect of vegetation structure on deposition due to the dominance of the effects of hydrodynamic forcings and other, unmeasured interacting factors influencing sediment settling and erosion in this environment, such as microtopography (Stribling et al., 2007) and/or bed shear strength characteristics (Howes et al., 2010). Theoretical and lab based flume experiments provide optimal conditions for the detection of vegetation effects, even if they are small, by minimising the naturally occurring variability in other hydrodynamic and geomorphological factors, leading to a possible overestimation of the role of vegetation structure on sedimentation *in situ* under some conditions.

During the duration of our experiment, the missing impact of the vegetation-mediated sedimentation could have been caused by the typically calm summer weather conditions and the wave attenuating impacts of the flume. Significant wave heights in the flume averaged 0.02 m (derived from the wave proxy, Table 2), which is ten times lower than the mean wave heights measured at the saltmarsh pioneer zone at this location over a ten-month period (Möller and Spencer, 2002). The long term climate record for East Anglia wind speeds shows the lowest wind speeds occur in July, and that the wind speeds measured during the experimental period (daily average of 10 to 21 km h^{-1}) are within the range of the long term average for this month. The calm conditions generated low vertical mixing of the water column and led to low vertical mixing of suspended sediments. This resulted in suspended sediment travelling primarily within the lower 5 cm of the water column. The removal of sediment from the flume during ebb flow indicates that there is a highly mobile sediment fraction which is resuspended after initial sedimentation (during flood flow). Our sediment profiler data indicates that this sediment fraction travelled very close to the marsh surface (below 5 cm above the marsh surface, Figure 6). Only the final vegetation cover cutting reduced the mean vegetation height to within this height. Therefore, the imposed changes in vegetation morphology are not likely to have influenced this peak suspended sediment fraction.

Estimated flow speeds in the flume were very low, with maximum rising and falling velocities of less than 1 cm s^{-1}, characteristic of saltmarshes (e.g. Christiansen et al., 2000). Despite removing most of the plant canopy within the flume, surface roughness following the final vegetation cut was still noticeably greater than that of an unvegetated mudflat. Thus it is likely that the turbulent energy and flow structure close to the bed, remained similar following the vegetation cuts. Previous studies have suggested that sediment deposition is more strongly linked with marsh topography rather than with vegetation structure (Coulombier et al., 2012), and it could be that locally more sheltered areas associated with variations in topography caused by belowground vegetation structures trigger sedimentation of the suspended sediment. Our study also supports previous findings (van Eerdt, 1985) that belowground biomass (which remained mostly intact following the aboveground biomass removal) plays an important role in increasing bed-shear strength and preventing erosion (as the cutting of the vegetation canopy in our experiment did not significantly affect sediment loss from the flume during the ebb part of the tidal cycle). In this context, a large scale flume study showed that significant wave dissipation still occurs even when the aboveground biomass of a saltmarsh platform is mowed (Möller et al., 2014).

The net sediment gain per tide was on average only 13 % of the sediment flux entering the flume (Fig. 4). Thus the trapping efficiency of the tidally advected material was significantly lower than the hypothetical maximum and lower than simulations of sediment trapping efficiency in East Anglian marshes, using the numerical mass-balance model MARSH-0D, which predict trapping efficiencies of ca. 50% (French, 2006). Our calculated positive sediment budget of 12 g m^{-2} day^{-1} roughly compares to a vertical accretion rate of 2.7 mm y^{-1} (bulk density of ρ = 1.6 g cm^{-3} was measured for this site, R Reef unpublished data). Long term accretion rates measured using surface elevation tables and marker horizons adjacent to the flume show a net accretion of 7.3 mm y^{-1} (T Spencer, unpublished data). The accretion rates we measured during calm summer days are lower than the long-term average, supporting previous findings that accretion can be seasonal (Spencer et al., 2012), with higher rates during the more energetic winter season, a period when sediment supply is also higher (Prandle et al., 1997). High rates of accretion can also occur during infrequent high energy events (Stumpf, 1983; Schuerch et al., 2013). Our comparison of sediment budgets calculated using filter trap data with those calculated using the sediment mass balance approach suggest that the widely-used filter trap method could overestimate accretion, due to a lower erosion rate from the filter than from the surrounding sediments and/or the sediment removal occurred from surfaces other than those represented by the filter paper.

In conclusion, our findings suggest that during calm summer conditions the rate of sediment trapping by saltmarshes is independent of vegetation height or biomass. This is most likely due to very weak vertical mixing of sediment in the water column during calm sea conditions and the high surface roughness and bed-shear stress due to below ground plant structures. Our conclusion provides support for the simplification of vegetation canopies in numerical models of surface accretion under some hydrodynamic conditions. However, during periods of higher wind/wave energy and stronger vertical mixing of suspended sediments, the role of canopy structure could prove significant.

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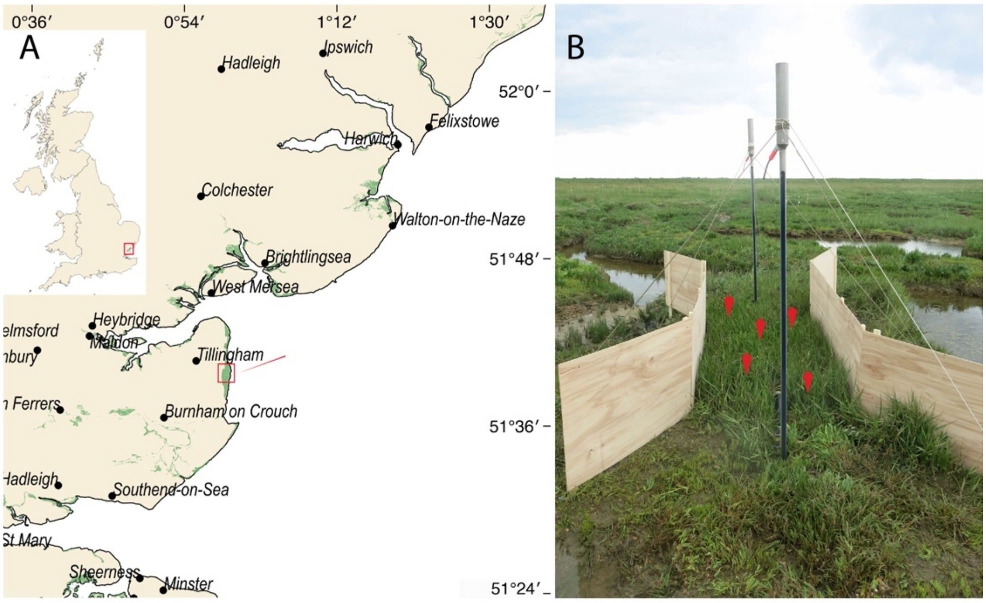

Figure 1: (a) The location of the study site near Tillingham, Essex, UK (51.69425°N 0.94206°E). Green shaded areas are saltmarshes. (b) a west-facing photo of the field flume, with the two ASM turbidity profilers and pressure sensors at the flume openings (the distance between the two ASM turbidity profilers was 1.82 m). Red markers point to the positions of the filters.

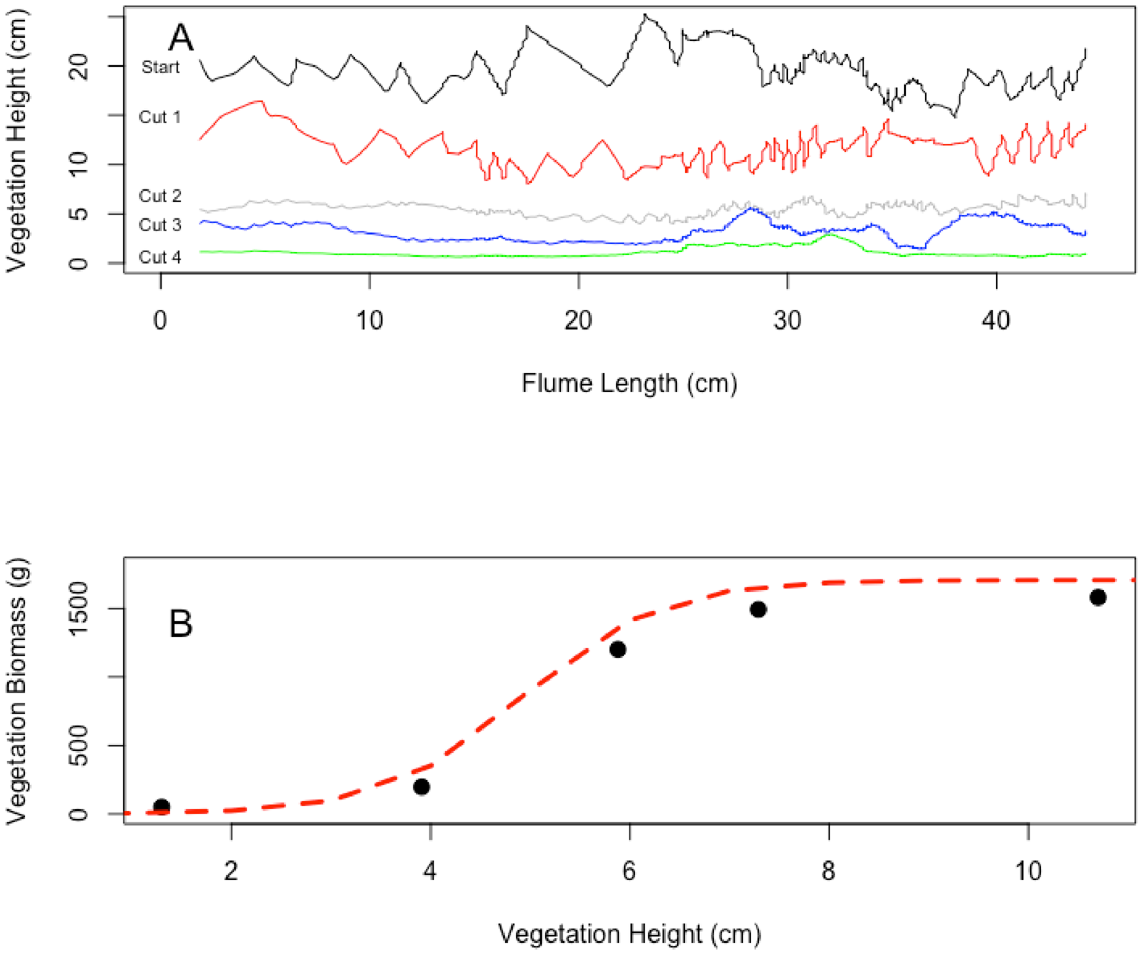

Figure 2: (a) A representative smoothed vegetation height profile along a section of the flume length for the initial conditions (Start) and subsequent vegetation cuts. The saltmarsh community within the flume was dominated by *Spartina alterniflora*, with an average stem density of 910 stems m^{-2} (b) the relationship between vegetation biomass and height is depicted by the logistic population growth function:

$$Biomass = \frac{2150 \times e^{1.46 \times Height}}{1707 + 1.26\left(e^{1.46 \times Height} - 1\right)}$$

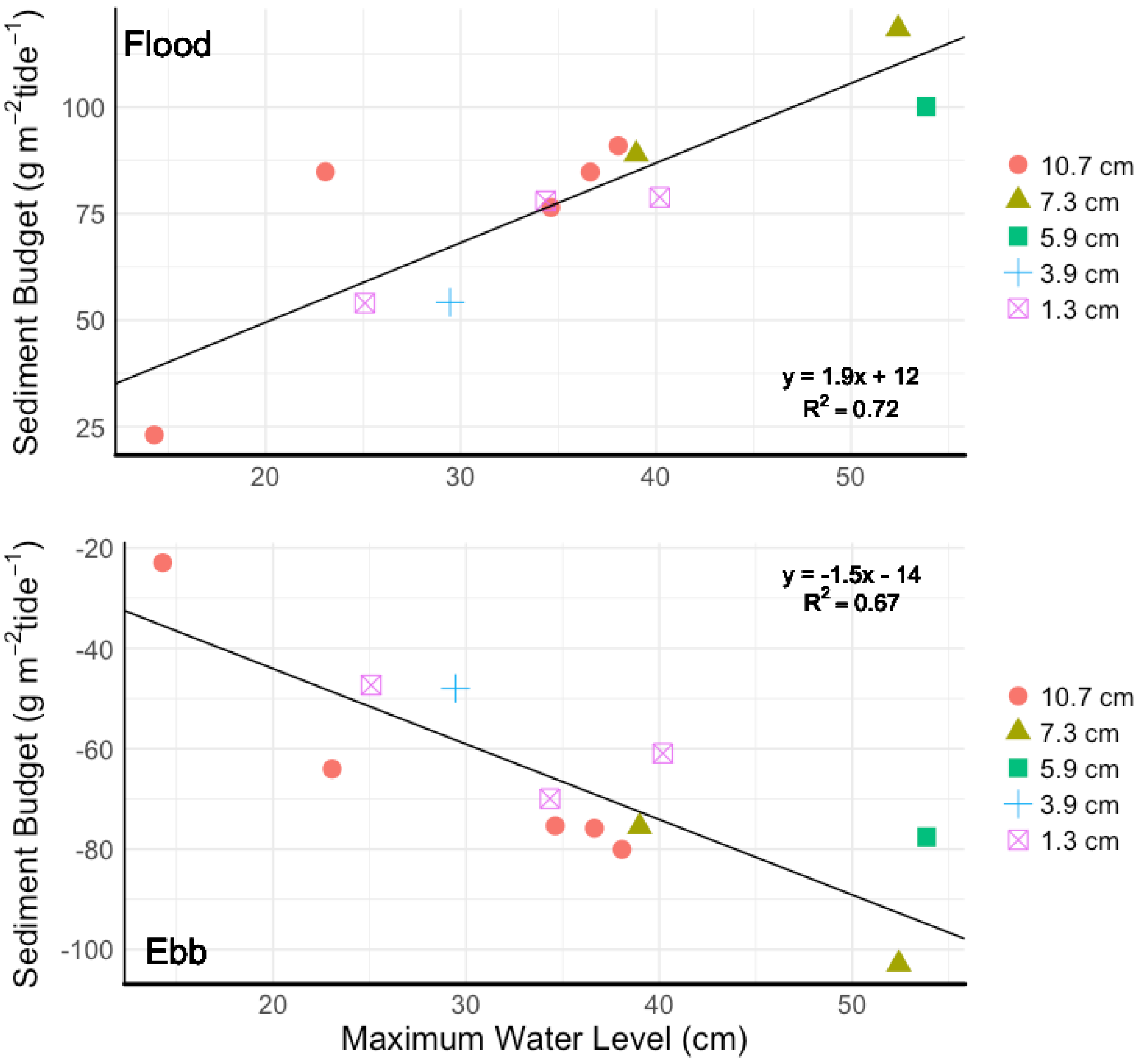

Figure 3: The sediment budget within the flume, calculated from the suspended sediment discharge between the upstream and downstream ASM sensors and the volume of water in the flume during the tidal period, as a function of maximum inundation depth (maximum water level during the tide) during the (a) flood and (b) ebb periods. Symbol shapes/colours correspond to different vegetation heights. A linear regression model was fitted to the data and the equation and fit are presented in the panels.

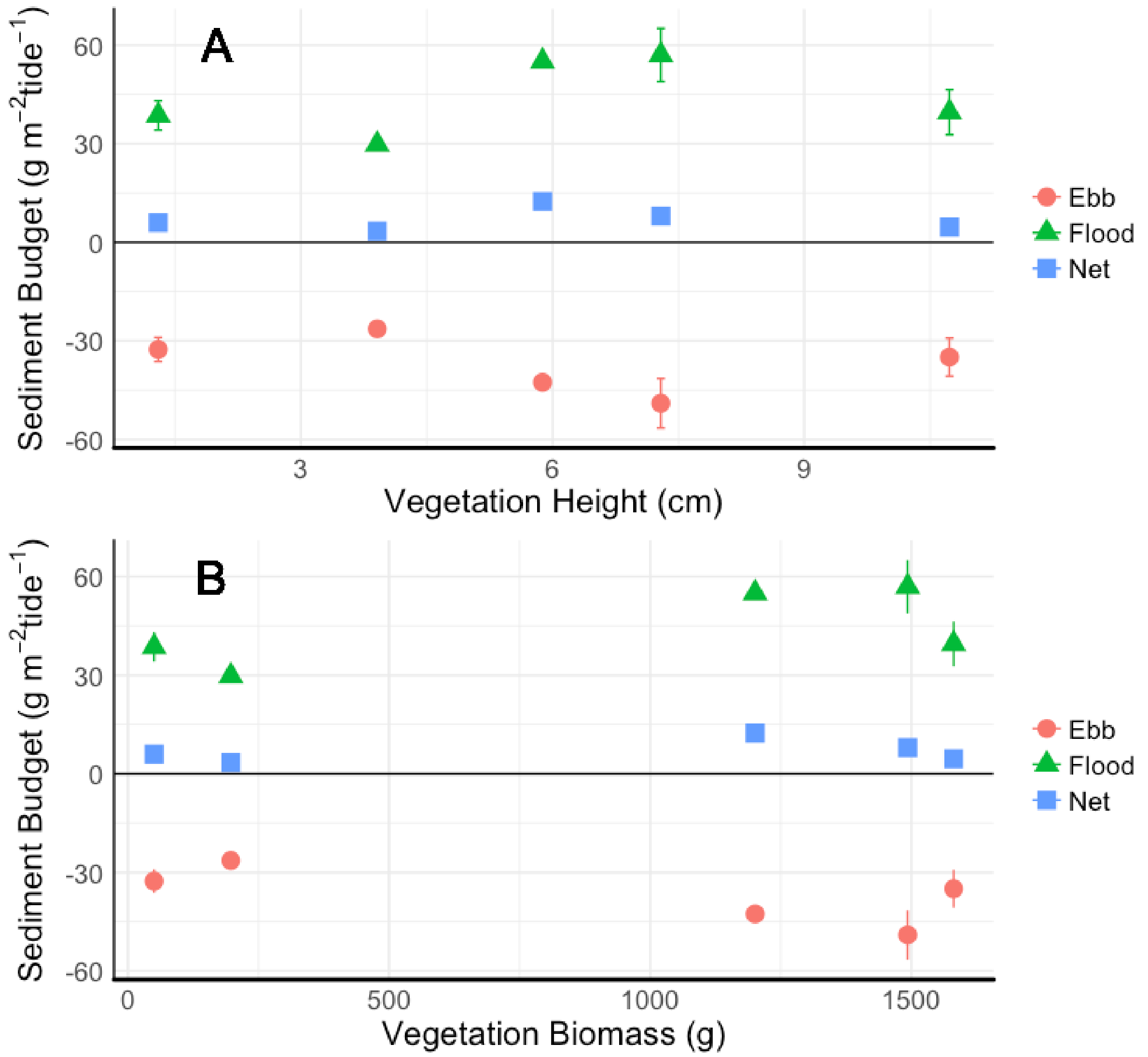

Figure 4: The mean (±SE) sediment budget within the flume, calculated from the difference in the depth-integrated suspended sediment concentration between the upstream and downstream ASM sensors (sediment discharge) and the volume of the water in the flume during the tidal period, as a function of (a) mean vegetation height and (b) vegetation biomass during the flood (green triangles) and ebb (red circles) periods. Blue squares are the mean sediment balance (±SE), with positive values indicating net sediment gain within the flume area and negative values, indicating net sediment loss from the flume area.

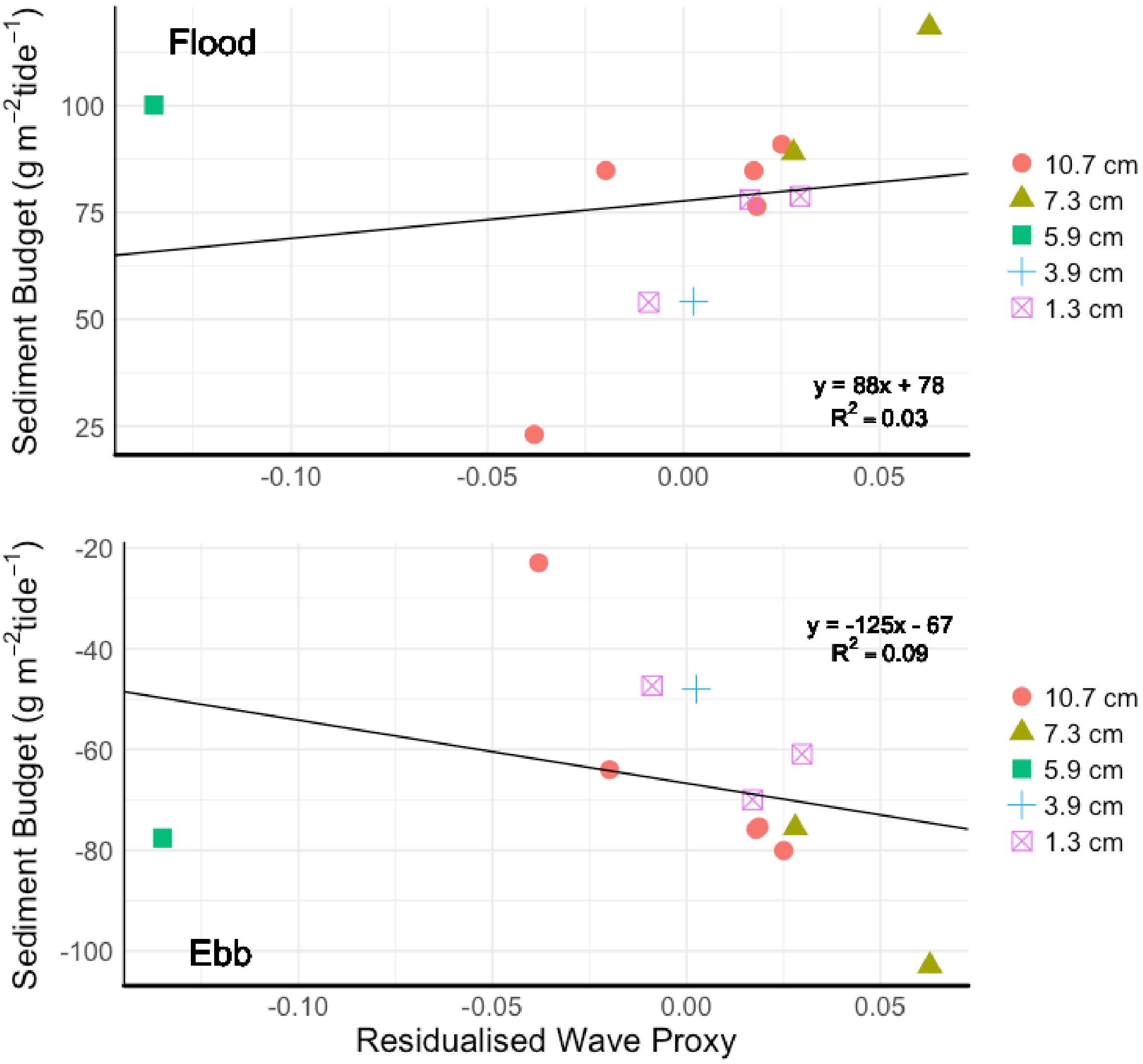

Figure 5: The effect of the residualised predictor wave proxy (corrected for the influence of maximum water level) on the sediment budget within the flume, calculated from the difference in suspended sediment concentration between the upstream and downstream ASM sensors (sediment discharge) and the volume of water in the flume during the tidal period, as a function of the wave proxy during the (a) flood and (b) ebb periods. Symbol shapes/colours correspond to different vegetation heights. A linear regression model was fitted to the data and the equation and fit are presented in the panels.

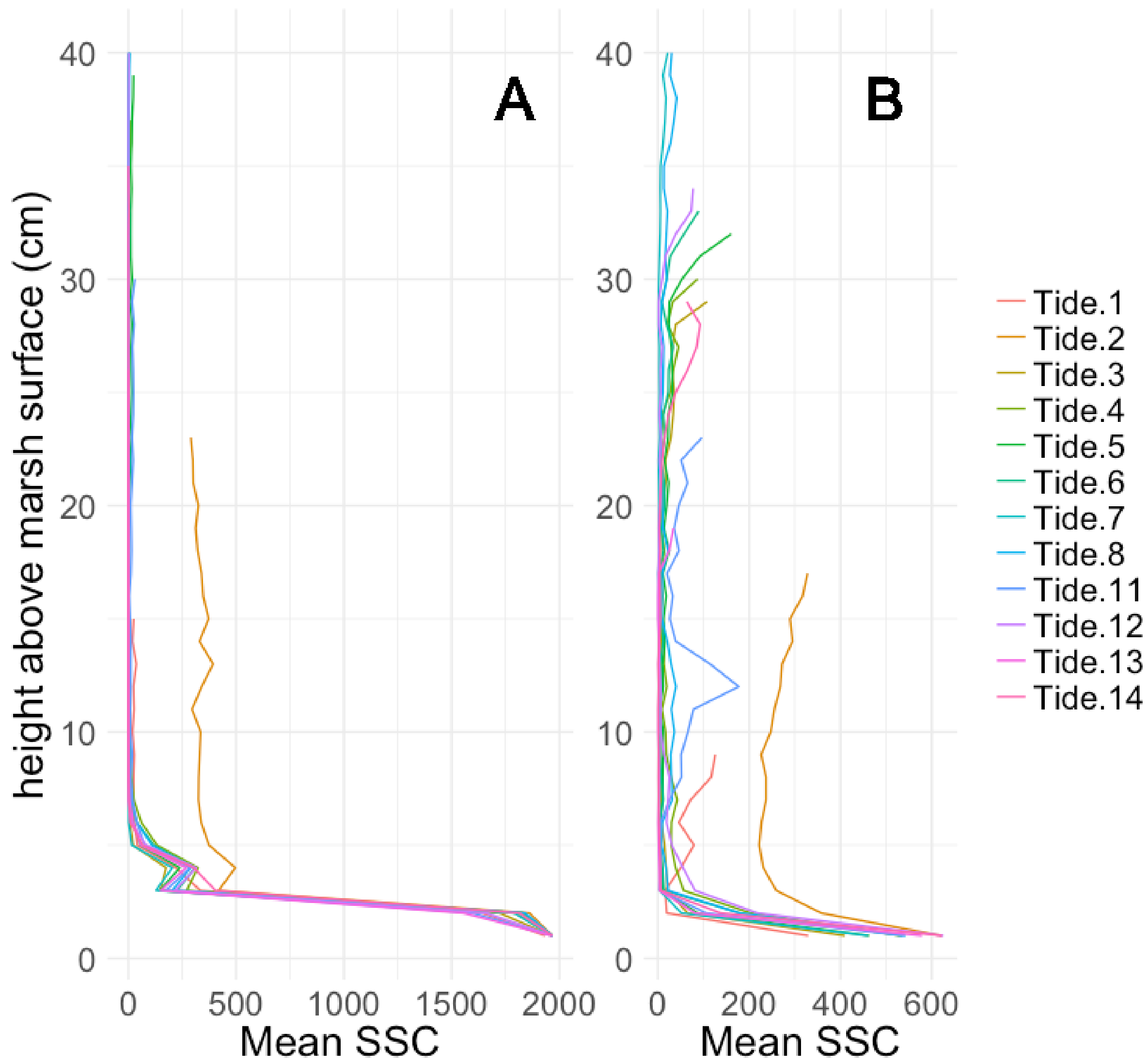

Figure 6: Suspended sediment concentrations (g m^{-3}) measured at different heights above the marsh surface at 1 cm intervals at the (a) seaward and (b) landward openings of the flume. Suspended sediment concentrations were much higher closer to the marsh surface (below 5 cm). Each line represents the mean for an entire inundation period for each sensor. The hydrodynamic conditions of each tide are described in Table 1.

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Figure S1: Calibration curves for the two ASM turbidity profilers used in the flume study. The 24 points of calibration were collected over a four-day period, immediately proceeding the flume experiment. Turbidity, measured by the ASM sensors, 4 cm above the marsh surface, was compared with sediment dry mass in 1 L water samples collected at the same time and from the same depth, using an ISCO automated water sampler and filtered on a GF/F filter. Both ASM sensors and the water sampler intake hose were placed together during the calibration period.